Int. J. New. Chem., 2021, Vol. 8, Issue 3, pp 298-328.

International Journal of New Chemistry

Published online July 2021 in [http://www.ijnc.ir/.](http://www.ijnc.ir/)

Open Access

Print ISSN: 2645-7236

Online ISSN: 2383-188x

Review Article

An Overview on the Carbon Utilization Technologies

With an approach to the negative emission construction material

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Received: 2020-03-13 **Accepted: 2020-06-21** **Published: 2021-07-01**

ABSTRACT

As an additional strategy to reduce carbon dioxide in carbon capture and storage, carbon sequestration, and utilization (CCU) is of great importance worldwide. Potential applications of the CCU range from using carbon dioxide in greenhouses and agriculture to converting carbon dioxide into fuels, chemicals, polymers, and building materials. CO_2 has been used for decades by advanced technologies in various industrial processes, including increased CO_2 recovery, food and beverage industries, urea production, water treatment, and firefighters' production and chillers. There are also many new technologies for using CO_2 in various stages of development and marketing. These technologies have the potential to create opportunities to provide emissions in power plants and other industrial sectors by replacing some raw materials for fossil fuels, increasing the efficiency and use of renewable energy, and generating revenue through the production of end-use products. This paper examines techniques for using carbon dioxide that convert carbon dioxide into commercial products through chemical and biochemical reactions with a focus on current technologies for broad supply or marketing. Carbon dioxide technologies are grouped according to technological conversion methods, such as electrochemical, photocatalysis and optical light, catalysis, biological processes (using microbes and enzymes), joint polymerization, and mineralization. In this paper, recent developments and the status of CO_2 technologies have been examined, and the environmental impacts of CCUs are also discussed in terms of life cycle analysis.

Keywords: CO_2 conversion; CO_2 to chemicals; CO_2 mineralization; negative emission materials; green concrete

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Introduction

Urgent action is needed to reduce greenhouse gas emissions. The most significant source of these activities is burning fossil fuels to generate electricity. Carbon capture and storage (CCS) is a device for generating low carbon electricity from fossil fuels and reducing carbon dioxide emissions from industrial processes such as gas processing and the cement and steel industry, which are other options for eliminating greenhouse gas. Therefore, the capture and storage of carbon dioxide are essential for achieving the goal of the Paris Agreement to limit global warming to less than 2 degrees Celsius. However, the implementation of CO_2 capture and storage technology requires huge capital and operating costs. Anything that can reduce the cost of the registration process and lead to a value-added product can significantly improve the economics of these systems.

As an alternative to underground burial for long-term storage, captured carbon dioxide can be used as raw materials to produce end-use products. Carbon dioxide has many potential applications, either directly or indirectly, through conversion. For decades, the direct use of carbon dioxide has been used in a wide range of industrial processes. These operations include refining oil with increased carbon dioxide (EOR), carbonated drinks, food processing, boiling, or as a cleaning agent in the textile and electronics industries and as a solvent (i.e., for the qualification of the Coffee and drinking water). These processes are usually mature technologies, supply-chain production, and demand chains are well established. Therefore, these processes are not discussed here.

Carbon dioxide can be converted into a wide range of commercial products, such as synthetic fuels, building materials, chemicals (either as end-use or intermediate products), and polymers. A range of CO_2 conversion technologies have been proposed and explored to produce these different end products. In 2015, 20 $ million from NRG COSIA Carbon XPRIZE was launched to compete in promoting the development of technologies that convert carbon dioxide into valuable products [4]. Ten finalists were chosen in 2018. The award helps identify the most promising paths for carbon dioxide conversion and shows that it can be deployed to power plants and other industrial facilities. The Top 10 Contestants must score at least ten times more than the semi-final requirements at one of two industrial testing sites created for this purpose. One is the

Wyoming Integrated Test Center (USA) stationed with a coal-fired power station, and the other is a new carbon conversion research center located with a natural gas power plant in Calgary, Canada [4].

There are many technological pathways for converting carbon dioxide into commercial products, such as catalysts, electrochemical, mineralization, biological (using microbes and enzymes), photosynthesis, and photosynthesis processes. Electrochemical reduction processes using electrolyzer reduction reaction to form chemicals from carbon dioxide and water. H_2, which is generally produced by electrolysis of water, is a conventional reactor for converting CO_2 to CH_4, CH_3OH, etc. and it worth mentioning that the electrolysis is energy-intensive and expensive. Compared to the well-established H_2O electrolysis, CO_2 electrolysis is a new research field that identifies low-cost, high-strength, high-efficiency, selective, and high-performance catalysts. When evaluated from a system-level perspective, energy efficiency, Farad efficiency, conversion rate, long-term catalyst stability, and operational economics are the five most important factors for commercializing these technologies.

The main difference between the CO_2 reductions and water reductions is the electrochemical stimulation in the electron source,, which is obtained from the radioactive semiconductor in the first one. The main advantage of photosynthesis is the direct use of photons, unlike the traditional conversion type,, which uses electricity. However, such processes are complex, involving many mechanisms such as electron and proton transport and the formation/breakdown of chemical bonds that are not well understood. The conversion of solar carbon dioxide-induced energy has attracted considerable attention worldwide, and research in this field mainly focuses on developing photocatalysts with new nanostructures and investigating the interaction mechanism of laboratory scales. For any method of using solar energy to convert carbon dioxide, efficiency is essential in terms of cost and scalability. Nowadays, achievable CO_2 conversion rates from developing photovoltaic/photocatalytic systems are often impossible for commercial-scale operations.

Since reducing electrochemical or catalytic carbon dioxide is a significant challenge for producing high-performance chemicals or fuels, it may be easier to use some well-established catalytic methods of reacting CO_2 and H_2 to produce carbon-based products. At the heart of this carbon dioxide,, conversion technologies are the catalyst - a material that converts carbon dioxide at high efficiency, selectivity, rapid reaction speed, and stability. Research and development are currently in the process all over the world to develop CO_2 catalysts. Several catalysts are designed, tested, and proven capable of converting carbon dioxide into various chemicals with high efficiency, selectivity, and high performance. Several reviews are describing recent developments in the design of the catalyst reactor [5-7]. More work is needed to make these catalysts more efficient, selective, and long-term stable. According to these catalysts, more work is needed to make technological and economic processes technically feasible to convert carbon dioxide into fuel and chemicals on a commercial scale. Also, one of the most critical technologies in the chemical and carbon dioxide fuel market is the low-cost production of carbon-neutral carbon dioxide [2]. In general, these processes require pure carbon dioxide, so carbon dioxide emitted from sources such as fossil fuels, steel, and cement plants need to be purified.

By using the appropriate enzymes or bacteria, carbon dioxide can be converted into chemicals through bio-activation. One of the benefits of biodegradation is that it is usually performed at low temperatures and pressures, so energy consumption is low. The process is generally simple and is mainly caused by bioreactors and the product separation/purification process resulting in lower costs. These processes can be extracted from emission sources without the need to purify the flue gas. However, biomass assay is generally a slow process. The key to biodegradable technologies is to find or engineer enzymes or bacteria to convert carbon dioxide into the desired product with high selectivity, efficiency, and rapid conversion speed.

Carbon dioxide can also be incorporated into many chemicals as a building block of C1, as in the co-polymerase CO_2-epoxide. This is not a problematic thermodynamic because the entire carbon dioxide molecule is used, and therefore the “C=O” bond is not broken. Dynamic and selective catalyst systems are critical technologies for the successful joint polymerization and economic success of carbon dioxide.

Ready-mixed concrete can be hardened by the carbonization process. Physical CO_2 refining involves reactions between calcium silicate in cement and CO_2 in the presence of water to form calcium carbonate and calcium silicate gel [8]. Carbonate reactions are shocked by heat. The heat released accelerates the baking process, reducing the need for heat or steam, and saving energy and emissions. Since much industrial solid wastes such as stainless steel slag, cement dust, concrete waste, and fly ash are generally alkaline, inorganic, calcium, or magnesium, by interacting with carbon dioxide, it can be used as a source that has been replaced as Ca or Mg for carbonization. In the presence of water to produce building materials. This type of technology has other environmental benefits, which means that both industrial solid and CO_2 are used and converted into end-use products. The carbonization process converts carbon dioxide into solid metal and permanently stores it in the end product. Given that concrete, after water is the most widely used material in the world, the possibility of reducing carbon dioxide in carbon dioxide technology to produce building materials is excellent. One of the main challenges facing the diffusion of carbon dioxide at the industrial level is to accelerate the slow carbonization process.

This article covers the latest CO_2 technologies that are grouped according to the technology pathways used. Given the vast and varied width of research and development, this study focuses on the pioneers of CCU technology that have reached commercial or pre-commercial stage or close to large-scale demos. These technologies have been attempted to make technology more advanced and less advanced. However, this arrangement does not necessarily represent the actual level of development of any technique, because in most cases, little is known about the processes and their performance for evaluating and comparing the techniques.

Electrochemical conversion of carbon dioxide

The electrochemical conversion of carbon dioxide was a dynamic field of research. Several possible pathways for converting CO_2 into products such as signage, methane, methanol, or dimethyl ether (DME) have been explored by combining renewable energy in the process. A German company, Sunfire GmbH, developed a mixture of electrolyte (H_2O) and CO_2 in a high-temperature process using solid oxide electrolysis (SOEC) cells to produce synthetic gas. These components can then be converted into synthetic fuels such as gasoline, diesel, and methane. SOEC operates at high pressure (> 1 MPa) and high temperature (> 800 ° C). They divide soda water (steam) into H_2 and O_2 instead of liquid water. Besides, H_2O and CO_2 electrolysis are more cost-effective due to the comprehensive rapid electrochemical mobility. In the Sunfire process, the singles are converted to Blue Crude by the Fischer-Tropsheet (-CH_2-) process known as Blue Crude to produce fuel or chemicals. The Fischer-Tropsch process is exothermic, and the liberated synthesis temperature can be used to evaporate the water for steam electrolysis (see Figure 1). This allows for a high level of efficiency (calculated to convert electrical energy into the amount of fuel produced) at 70% [1, 10].

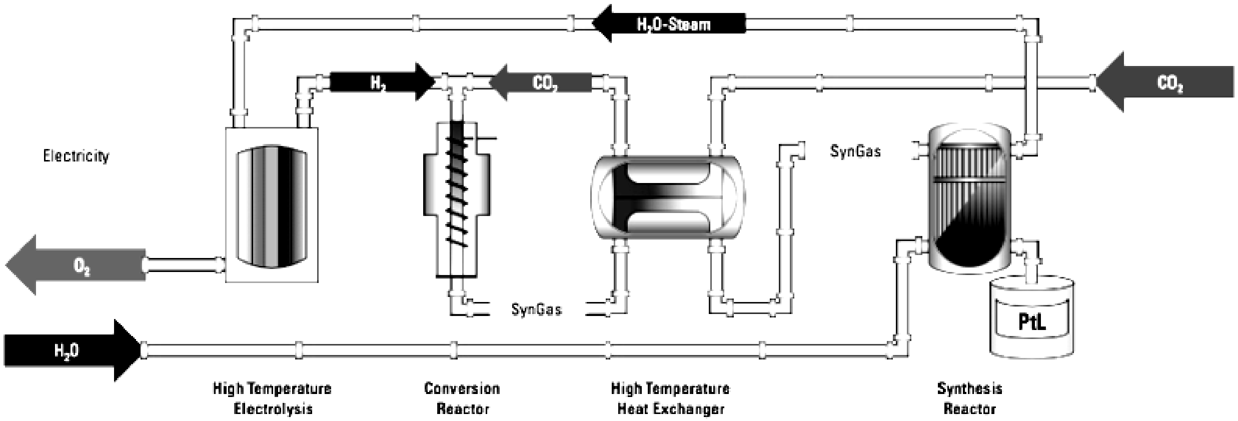

Figure 1. diesel from water, air-captured CO_2, and green electricity; "Blue Crude."

Sunfire GmbH built a test plant in Dresden, Germany, that produced the first batch of high-quality diesel fuel in April 2015 [11]. The 10 kW electrolyzer operates at 1.5 MPa and can be adjusted from 0 to 100% without negatively affecting the stack. The test plant has been running continuously for over 1500 hours and has achieved 90% carbon conversion efficiency. Synthetic fuel (diesel Audi) has a high interruption value and therefore has excellent combustion properties [1, 11]. In July 2017, Sunfire GmbH announced that it had started engineering the PtL plant in Norway with a group of partners. Nordic Blue Crude AS, a Norwegian clean technology company, will operate 20 MW PtL with a production capacity of 8,000 tons/year of raw blue water and is expected to start operating in 2020.

Another German company, ETOGAS, has developed a process that uses H_2O alkaline electrolysis to produce H_2, which then reacts with CO_2 to form CH_4 [1]. The system was developed based on the dynamic and disconnected photoelectric (PV) function associated with alkaline electrolysis. The direct connection between PV generators and alkaline electrolyzers has been successfully connected in different energy ranges. Methane catalysts mainly consist of nickel, which is the material used in the electrodes for electrolysis and may reduce the cost of materials. ETOGAS has a 25-kilowatt test plant in Bad Hersfeld to test biogas upgrades and install 250 kilowatts in Stuttgart. ETOGAS has built a 6-megawatt gas-fired power plant (PtG) for German automaker Audi AG in Werlte, Germany, starting in 2013. Since 2013 this plant is operating in a dynamic and intermittent process using wind energy and carbon dioxide from the biogas plant. The plant can produce about 1,000 tons per year of Audi gas, resulting in chemical storing about 2,800 tons of carbon dioxide. Audi e-gas contains methane content> 96% and is available to Audi A3-Tron g customers. By increasing the number of electrolysis units, the unit size can be increased [1, 5, 13]. Figure 2 illustrates the energy efficiency of the PtG process.

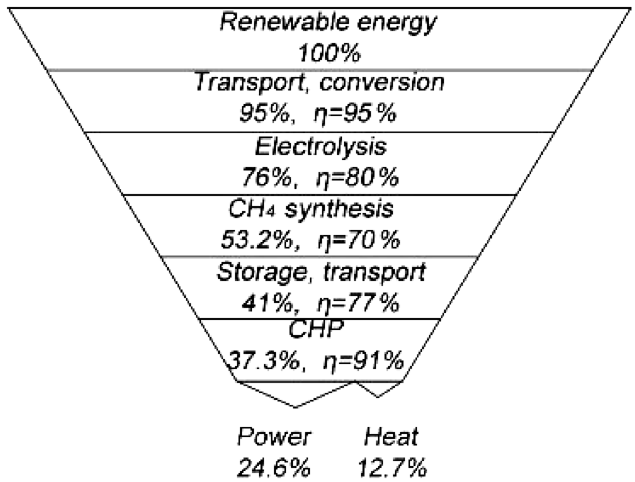

Figure 2. Process chain for power storage systems methane. [13]

In December 2017, Hitachi Zuzen Innova AG (HZI acquired ETOGAS Technology in 2016), with parent company Hitachi Zuzen Corporation, as part of an effort to build the first PtG pilot plant in Japan as part of Japan's effort to achieve a long-term reduction in Carbon dioxide emissions. The plant is responsible for fossil carbon dioxide emissions and combines carbon dioxide with H_2 to produce methane, which is then fed into an existing gas network. Hitachi Zuzen offers electrostatic exchange polymer membrane to produce H_2. HZI provides the ETOGAS catalytic reactor for the mining process. This pilot project is expected to start operating in 2018/2019 [28].

The Danish company Haldor Topsøe developed a methane process called TREMP [5]. The process involves three fixed-temperature bed reactors using household methane catalysts. The heat recovered from the chemical transformation process is used to generate the high-temperature steam required in the SOEC unit. Haldor Topsøe built a 40-kilowatt SOEC unit in Volum, Denmark. In 2016, they developed a highly efficient process with a CH_4 output of 10 m^3/hour, as shown in Figure 3, to upgrade biogas containing carbon dioxide (50-80%) into the high-quality natural gas (methane). The overall efficiency of converting electric energy into methane is about 80% (see Figure 4). Therefore, energy consumption is prevented by 290 kW/tonCO_2, and also freshwater consumption is about 1.6 ton/tonCO_2, and there is no other flow or emission from this process [1, 5, 15].

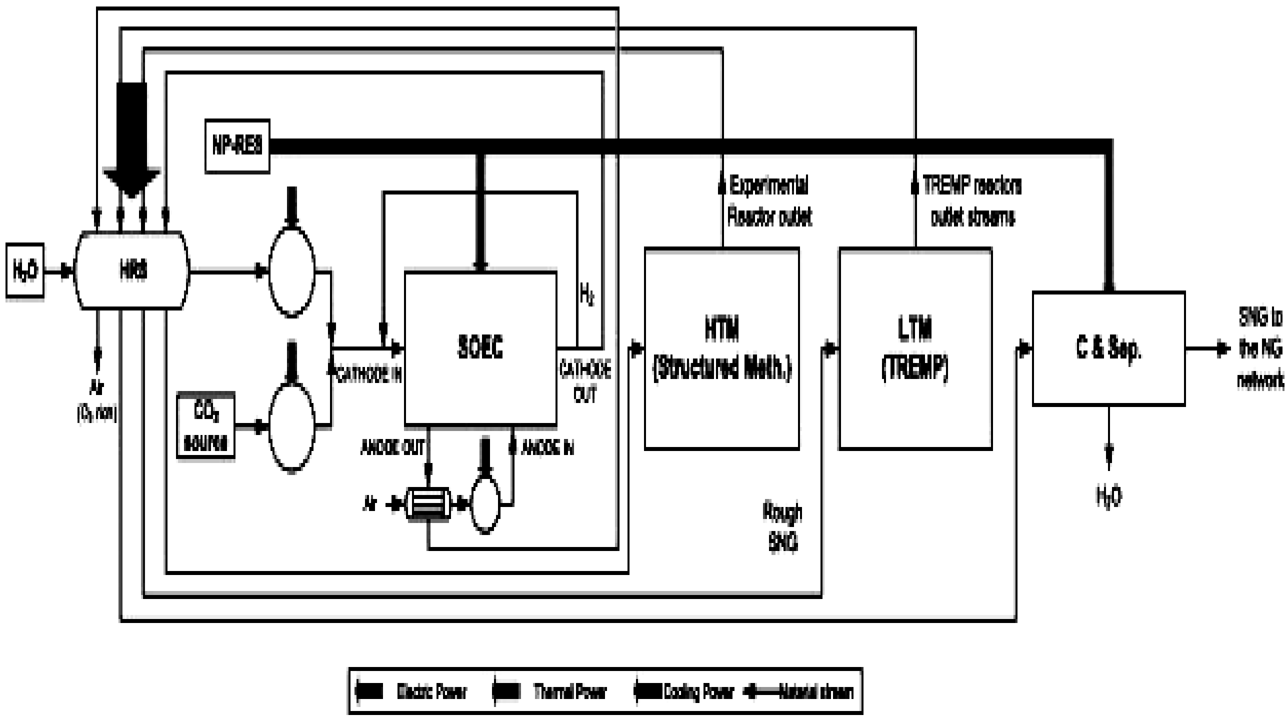

Figure 3. Thermal integration of a high-temperature co-electrolyzer[5]

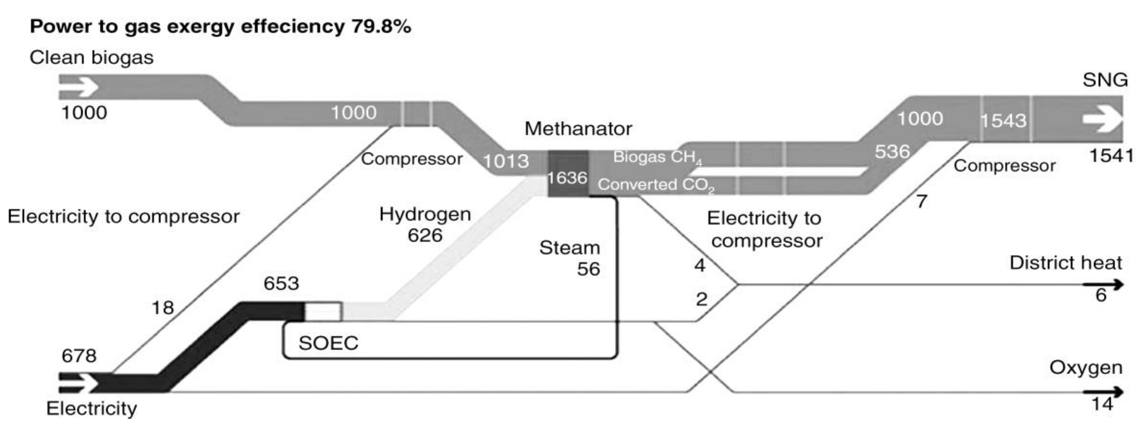

Figure 4. Exergy of Haldor Topsøe system [12]

Haldor Topsøe also developed a process called eCOs that was developed to generate SNG from carbon dioxide and electricity using SOEC [15]. ECOs are designed as a process as modules that can be combined into a plant with a capacity of 25 to several hundred cubic meters per hour.

The Norwegian company DNV GL developed the ECFORM process to convert CO_2 to formic acid (FA). The ECFORM process contains the new electrolysis reactor, as shown in Figure 5. A proprietary tin alloy catalyst is used as a cathode to convert carbon dioxide to form FA. The reactor has less cellular capacity and less waste resistance, thus increasing the energy efficiency in the process, making it more economical [17]. Test results show that the electrodes have a choice of 75% for 1-2-year operating time. The cell's energy consumption is 5.5 pounds per hour, and this process can depend on renewable energy [18]. DNV GL built an ECFORM semi-experimental demonstration reactor with an area of 600 cm^2 and a reduced capacity of about 1 $kgCO_2$/day. From 1 tonne of CO_2, this process produces 1.04 tons of formic acid at least 85% by weight distillation, which practically indicates a 1:1 decrease in CO_2 reduction [1, 17]. This is a preparatory process to scale up, but significant technological progress is needed before large-scale production occurs.

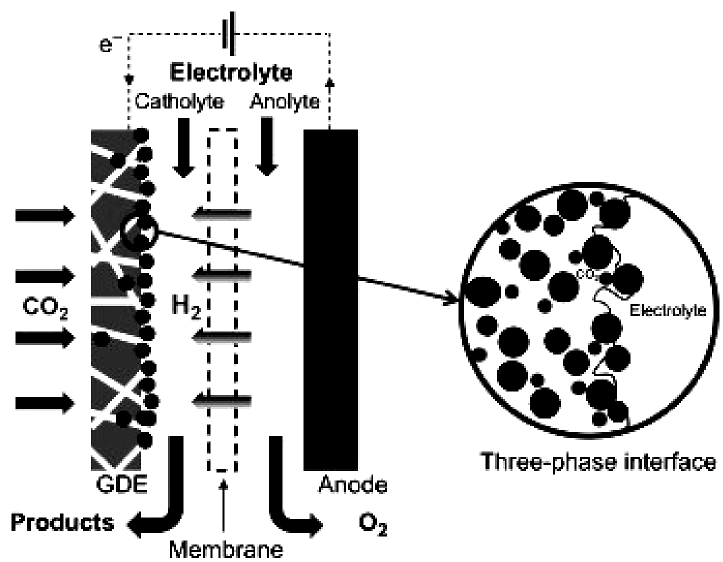

Figure 5. Electrochemical Conversion of CO_2 [18]

A team at George Washington University in the USA is developing a C2CNT process that can convert carbon dioxide into high-value carbon nanofibers (CNFs) and low-voltage electrodes (nickel and steel) carbon nanoparticles. Carbon compounds have a variety of applications, including batteries, electronics, and lightweight metal alternatives that are used today in aircraft, advanced sports cars, and sports equipment. In the C2CNT process, carbon dioxide is dissolved in a molten carbon bubble. CO_2 is divided by electrolysis of the electrodes immersed in the molten bath into O_2 in the anode and the pure carbon nanotubes in the cathode. By adjusting various parameters such as adding trace transitional minerals as CNF base sites, adding zinc as principles, and controlling current density, the composition of CNF or carbon nanotubes can be controlled, and product structure can be modified. And for a specific application, such as the anodes in the lithium batteries and sodium ion.

The C2CNT process can be used to capture CO_2 directly from a variety of sources, including the atmosphere, power plants, and cement plants. The researchers proposed plans to adapt the system to natural gas and coal plants, which absorb large amounts of carbon dioxide and convert it into carbon nanotubes and pure oxygen. The oxygen can then be used to enhance combustion, and the plant does not contain any carbon dioxide emissions [21]. The analysis shows that carbon nanotube production can be more profitable for fossil fuel power plants than electricity generation. For every ton of spent natural gas, the combined conventional gas station (NGCC) generates 909 $ and generates 2.74 tons of carbon dioxide, while the proposed combined NGCC and C2CNT generate an additional 0.75 $ electricity and 835 $ by-products. The cost of producing carbon nanotubes is estimated at 2,000 $/tonne, which is less than 1% of current production costs Using the C2CNT process [22]. Although costs are determined by developing and marketing C2CNT and reducing the availability of large quantities of low-cost nanotubes on the market, there is potential for profit, which makes this technology attractive and reduces the power consumption and emission of the energy industry. The C2CNT team is one of 10 finalists in the NRG COSIA Carbon XPRIZE Award [4]. Researchers are currently trying to extend and clarify the C2CNT process.

The Sunfire and ETOGAS process has been demonstrated on a test scale, and developers are confident that they will expand their range to suit small industrial production. ETOGAS CH_3OH is produced as an end product, while Sunfire has the flexibility to produce various products because it produces synchronization as a medium. ECFORM, C2CNT, and Haldor Topsø processes require more research and development work to be presented more widely.

Photocatalyst conversion and carbon dioxide photovoltaic

The conversion of solar energy from carbon dioxide into solar energy has received worldwide attention. The marked improvement is a prototype of the "Sunshine to Petrol" reactor (S2P) recently demonstrated by the US Department of Energy's Sandia National Laboratories (SNL) [23, 24]. S2P uses two-stage metal oxide-based cycles (CO and H_2) to produce CO_2 and H_2O. The core of the S2P process is a unique biochemical engine based on a metal oxide called the Circular Reactor of the Reactor Reactor (CR5), which features continuous flow, product separation, and thermal recovery. Within the engine, the reactive solid rings are rotated thermally and chemically to produce separate O_2 and CO from CO_2 or O_2 and H_2 from H_2O (see Figure 6). CR5 cylindrical metal is divided into hot and cold rooms. The solar center warms the reactive material of ceramic oxide on a rotating ring to 1500 ° C (2,700 ° F), thermally reduces it, and turns off some oxygen. Then the ring is rotated to a CO_2 filled heatsink. When cooling, the hypoxic reactant is oxidized by CO_2 to restore it to its original state and restore CO_2. This cycle is repeated continuously. The same process can also produce H_2O by pumping H_2O instead of CO_2 into the cold chamber. H_2 and CO are then mixed to form an individual, which can be converted to almost any type of hydrocarbon fuel [23].

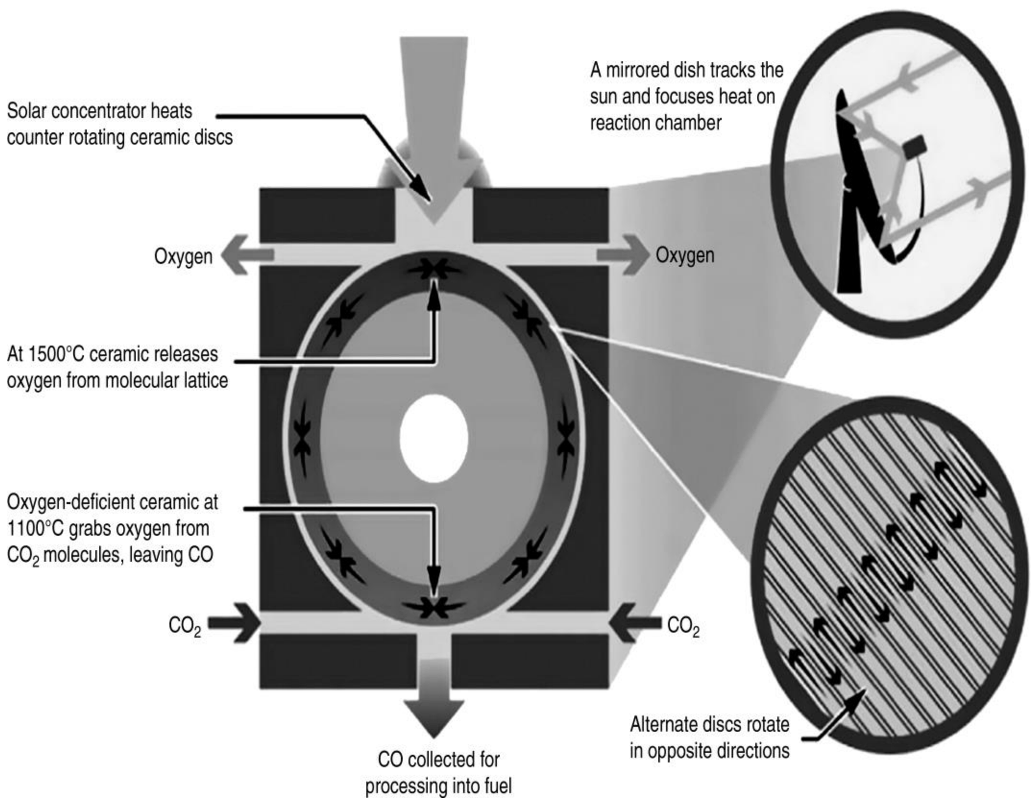

Figure 6. Counter-rotating-ring receiver/reactor/recuperator (CR5)

The multi-side production of H_2 and CO is shown on many cerium-based compounds made in integrated components in both SNL and the National Solar Thermal Center (USA). These vehicles are produced for publication on the CR5 prototype. Continued work on materials, development of reactors, and sustainable performance offer led to the production of a second-generation CR5 and a more efficient and compact reactor. The new reactor is constantly operating, producing carbon dioxide with a maximum efficiency of 1.7% CO_2, and recently achieved H_2 production at 2 liters per hour [24, 25]. However, catalysts and structural materials that have been developed so far are not able to support enough efficiency sufficiently that this technique can outperform other methods such as electrolysis. However, SNL's work provided evidence of the technology's potential [6, 7].

catalytic conversion of carbon dioxide

In 2012, Iceland's International Carbon Recovery (CRI) commissioned the world's first carbon dioxide production facility with a current capacity of 5 million liters per year (4,000 tons per year) of methanol (Vulcanol ed brand)[26]. Vulcanol is also used as a mixture of gasoline and converted into a diesel alternative. Carbon dioxide is released from the flue gas from the geothermal power station adjacent to the CRI facility. The plant now generates 5500 tCO_2 a year, which is released to the atmosphere. All of the energy used in the plant comes from the Icelandic grid, which is supplied with hydro and geothermal energy. CRI Liquid Technology (ETL) patented technology includes a low-pressure alkaline electrolysis system for H_2 production and catalytic fuel stimulation process. Carbon dioxide passes through the gas conditioning system in which impurities are removed to produce the appropriate carbon dioxide to form the final methanol. H_2 and CO_2 are mixed in a 3:1 ratio and pressurize the target pressure, followed by the catalytic synthesis at a high temperature to produce methanol. By increasing the number of electrolysis cells, the units can be smaller. The reaction is hugely exothermic and is recovered and used in the subsequent distillation unit, where the produced methanol is mixed to mix with gasoline to the fuel grade. Figure 7 shows the mass, energy, and overall efficiency of the ETL process.

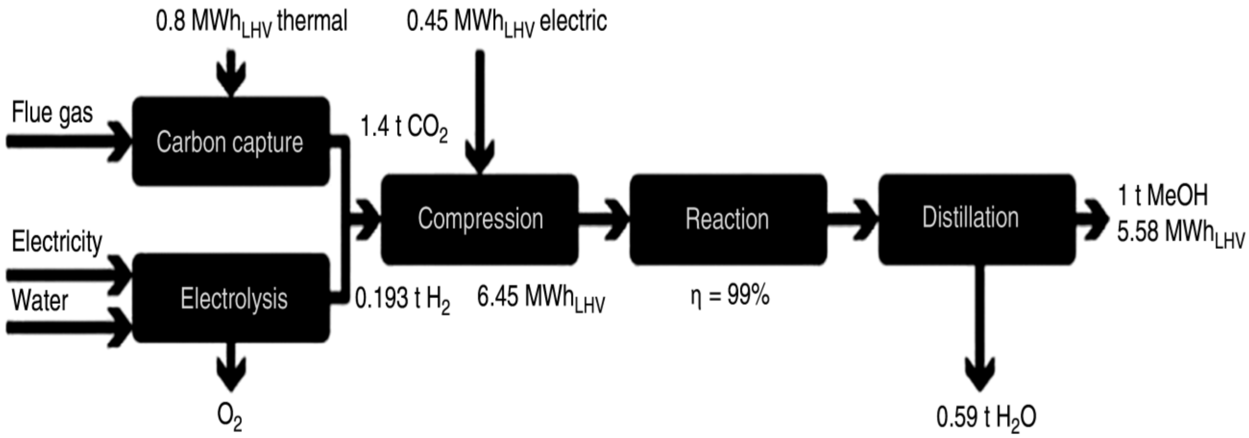

Figure 7. the ETL process [27]

CRI and a group of European industrial research institutes and companies have received 11 million euros in funding from the European Union's Horizon 2020 program to implement ETL CRI technology at a Swedish steel plant and convert the carbon emission into gas [26], [27].

A Canadian Carbon Engineering Company (CE) is developing and trading its A2F fuel systems [28]. A2F uses direct air capture (DAC) technology with electrolysis of water and fuel synthesis to produce liquid hydrocarbon fuels (see Figure 8). First, the DAC process extracts carbon dioxide from the air. The CO_2 is then purified and compressed into the liquid and ready to be used. Second, clean electricity (such as solar PV) is used to analyze water and produce hydrogen. Third, carbon dioxide and hydrogen interact with the heat individually to produce components that are then converted into hydrocarbons such as diesel and jet fuel.

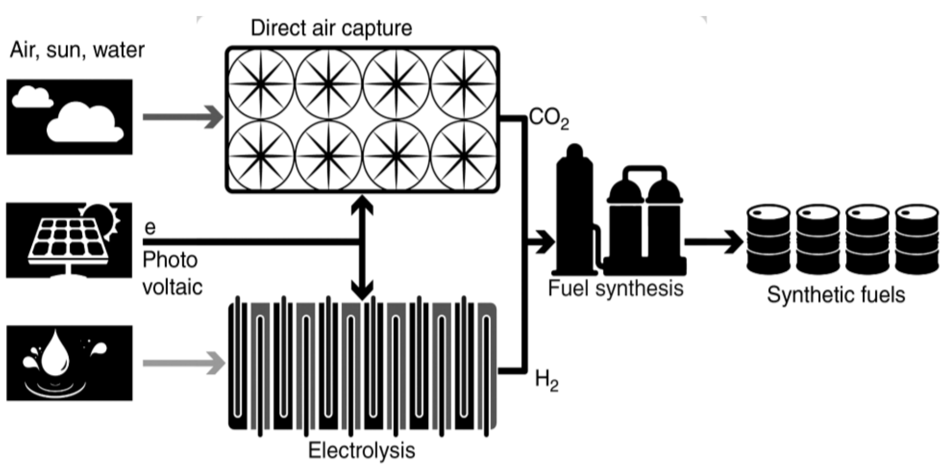

Figure 8. A2F CE process diagram [28]

CE has chosen the direct fuel production platform as a fuel blending technology. The direct fueling platform, shown in Figure 9, was developed by an American company called Greyrock, using a particular catalyst and processor to deliver methane-rich steam (coal mine, single flame gas activation). Natural gas or liquefied natural gas) to premium diesel fuel. Platinum-based metal catalysts can directly convert methane-rich gas into premium fuel, “drop,” and put in place an expensive refining step in line with the traditional Fisher Turbist process, and thus economic viability. It provides reasonable prices. The scale of gas to liquid installations [29].

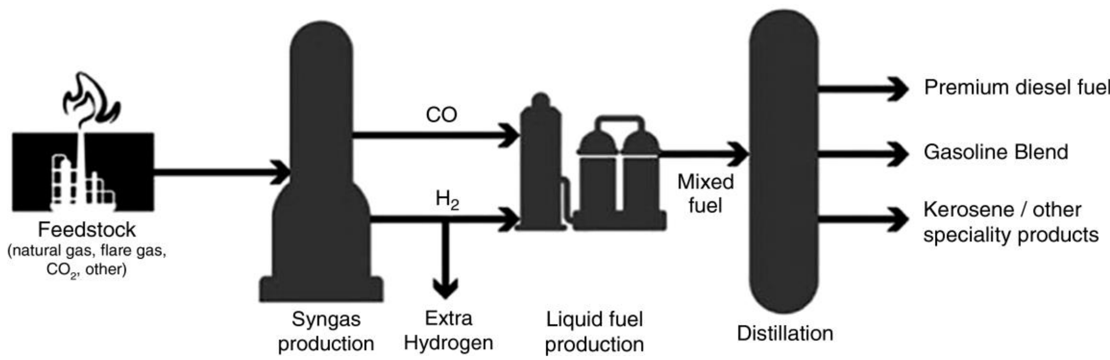

Figure 9. A2F CE process diagram [29]

In 2015, CE launched a DAC pilot plant that captures and purifies 1 tCO2/day from the atmosphere. In 2017, electrolysis of water and a Greyrock M-Class fuel station was installed with the ability to collect approximately 1 barrel of fuel. In December 2017, the A2F system successfully produced the first quantities of liquid fuel [28]. The A2F process uses proven technologies, and the integrated system has proven to work well on a small scale. The system is expected to be scalable without major engineering hurdles. The main disadvantages are the large footprint and the high cost.

BSE Engineering (Germany) is developing a flexible and sustainable process for the production of methanol from CO_2 and H_2 (see Figure 10). The process uses an alkaline electrolyzer and additional renewable electricity to generate H_2 in an oscillating state of operation. The captured and purified carbon dioxide is fed with H_2 in a reactor suitably proportional to methanol production through the catalytic reaction and heat dissipation. The reaction temperature is recovered as vapor and used in the methanol purification process. The raw reactor product contains 64% CH_3OH and 36% H_2O, which is purified by distillation to a final CH_3OH product> 99.85% by weight. Water electrolysis and methanol synthesis have a high elasticity ranging from

10 to 120% [30].

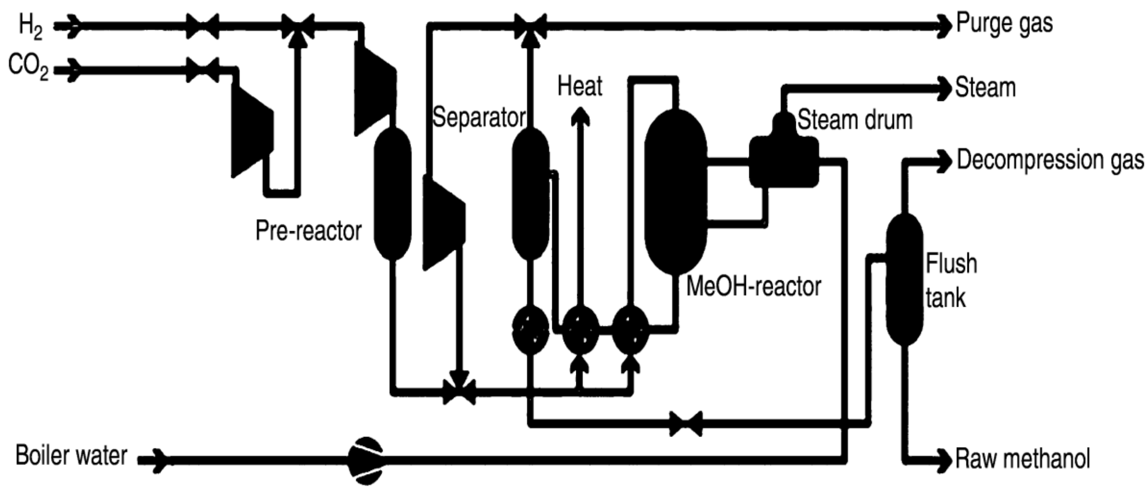

Figure 10. BSE Engineering Engineering methanol manufacturing process: catalytic reaction to CO_2 (1.36 t/h) and H_2 (0.19 t/h) to raw methanol (1.55 t/h) [30]

BSE Engineering recently conducted a demonstration project in which various catalysts were tested. In August 2017, BSE Engineering and BASF (Germany) signed a BASF patent development agreement to provide catalysts specifically for the methanol manufacturing process to enable efficient methanol production [31]. BSE Engineering expects the first assumption of a 10 MW power plant to methanol in 20/20/2019.

Bioconversion of CO_2

Several interesting biomarkers are also being developed using CO/CO_2, some of them on an industrial scale. LanzaTech has developed a biogas fermentation process that uses exhaust gases from industrial processes to produce fuel and chemicals [32]. This process converts waste gases and residues rich in carbon dioxide into a chemical in a continuous process using microbes that grow on gases (instead of sugars, like traditional fermentation). LanzaTech owned bacteria are a natural organism that occurs in the estrogenic family or benzene fermenting organisms that can digest a wide range of carbon-rich wastes for selection, fuel, and chemicals such as ethanol and 2,3-butanediol products. This process can consume carbon dioxide-free gas streams containing carbon dioxide due to the highly efficient biogas exchange of water in estrogenic microbes. This reaction to bacteria can offset any part of H_2 in the inlet gas stream by stimulating the release of H_2 from water using CO energy.

Consequently, the LanzaTech process is flexible in terms of raw materials and can be produced by flue gas with a wide range of CO and H_2 compounds [1, 32]. The LanzaTech process is simple (see Figure 11) and works near ambient temperature and air pressure, thus reducing carbon dioxide emissions and reducing heating and cooling costs. Two energy sources are used: steam to separate/purify the final product and electricity to carry out process equipment such as pumps and compressors.

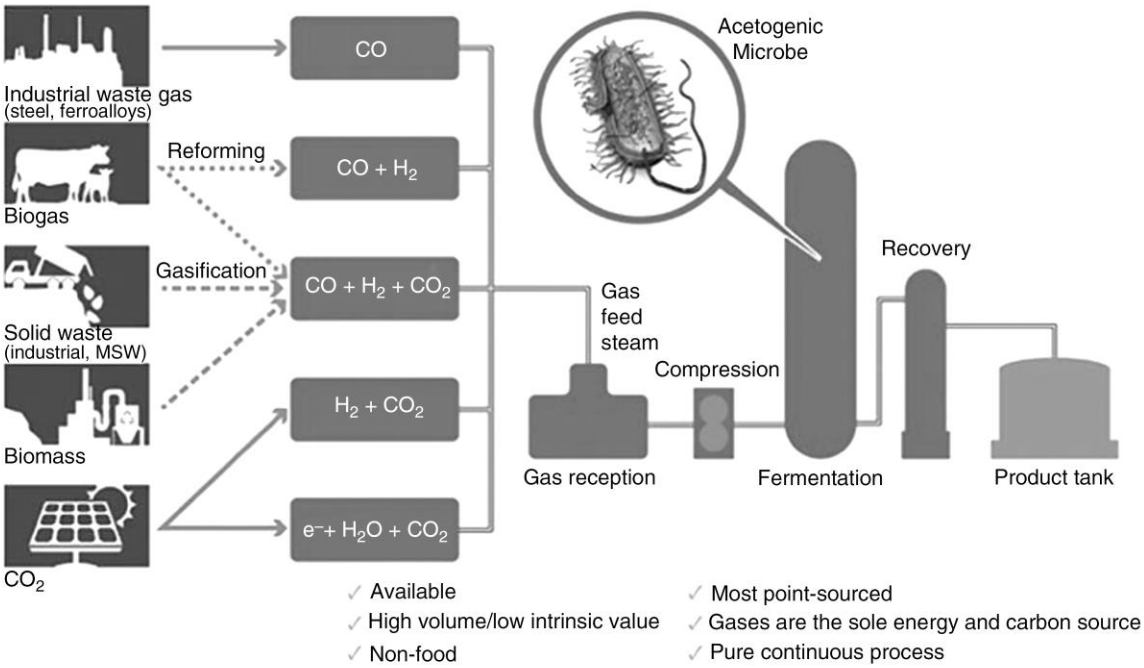

Figure 11. gas-fermentation process[32]

In 2008, LanzaTech started the experimental production of ethanol on a trial scale with a capacity of 56.8 cubic meters per year using off-gas exhaust from a steel plant in 2008. In November 2012, LanzaTech launched a 380 cubic meter display station with the largest steel producer in China, Baogang, in Shanghai. CO-rich flue gas is converted from ethanol to Baogang Steel Plant. The second display plant has been built on equal footing in Shogun Iron Factory in Beijing and has been operating since 2013. The facility operates with flue gas, which has a high carbon dioxide content and does not contain H_2, reaching> 1000 continuous hours. Operations at a production rate of 400 cubic meters per year. Additional non-metallic gas feeding facilities with a steel capacity of 46.2 m^3/ethanol were introduced in 2014 in Kaohsiung, Taiwan. In 2013, LanzaTech commissioned a display plant in Georgia (US) using biomass syngas to remove gas for ethanol production. In 2014, LanzaTech, along with the Japanese Sekisui

Chemical, using the LanzaTech process, demonstrated the production of ethanol using municipal solid waste (MSW). Sekisui MSW Processing Plant is a commercial plant that gases MSW non-recyclable, non-recyclable, and non-recyclable liquids, and the resulting individual is burned to generate electricity. Glide stream from 1:1 H^2 Singles containing CO was fed to LanzaTech bioreactor to produce ethanol continuously, several times for 12 months. These features outline the different vital aspects of the LanzaTech process [32, 33]. LanzaTech's first commercial facility started producing ethanol steel waste to 60 567 cubic meters annually, and it was operating in China in May 2018, and many other offshore steel mills are planning ethanol or under construction in China. Belgium (90850 cubic meters per year). The LanzaTech plant that converts alloy exhaust gas to ethanol with a capacity of 53212 cubic meters annually is scheduled to operate in 2019 in South Africa [32, 33].

LanzaTech is also developing a fermentation process that can use carbon dioxide as a carbon source. Currently, they partner with IndianOil to build the world's first bio-ethanol refinery. The demonstration will install 40000 cubic meters annually (35000 tons annually) at the Indian Oil Banipat refinery at an estimated cost of 350 billion Rs (the US 55 million $). It will be integrated into the site infrastructure and will be the first LanzaTech project to capture outdoor refineries [33]. The filtered exhaust contains almost equal amounts of carbon dioxide, and carbon monoxide contains a large amount of H_2 (H_2:CO ratio 5:1). Fifty percent of the carbon in the ethanol product comes directly from carbon dioxide. The plant will be launched in 2019 [33]. As described above, the LanzaTech process using synthesis gas rich in carbon dioxide or gas from various sources has been successfully demonstrated on a pre-trade scale. Several commercial projects are under construction and planned. Work is underway to create a system that can convert carbon dioxide into efficiency and economy.

An American company, Joule Unlimited Technologies Inc. Microbes such as genetically engineered blue bacteria that inhibit the sun's energy to convert CO_2 and H_2O directly into ethanol fuel or hydrocarbons were produced in a continuous one-step conversion process. This technology is facilitated by the patented Joule SolarConverter system, which uses threaded circulation units in the form of thin, standard capsules filled with their microorganisms, non-potable water, and micronutrients. Cyanobacteria are grown in non-potable water, carbon dioxide waste is produced from local sources of chimneys and industrial gases, and fertilizers are fed into capsules to promote growth. Microorganisms were moving to maximize sunlight and direct photosynthesis. Solar-powered microorganisms absorb carbon dioxide and produce fuel molecules that are transported continuously to the environment. The final product was extracted through a separator that was eventually sent to the central plant to separate and purify the fuel grade [34]. This process lasted up to 8 weeks, after which the units were washed and cycled. The process is designed to convert carbon dioxide emitted from power plants and industrial processes through the presence of catalysts into a particle of particular importance, including ethanol, diesel, hydrocarbons, jet fuel, and gasoline. There was no need for pre-treatment of CO_2 flue gases [34, 35]. Joules has performed experimental diesel and ethanol production for two years (Sunflow-D and Sunflow-E brands respectively) and has approval to the US Environmental Protection Agency (EPA) agreed with Sunflow-E as an advanced biofuel annually received 2016 [34].

Joule's target for both Sunflow-E and Sunflow-D products is 0.32 $/liter (1.20 $ per gallon) or 50 $ per barrel. [35] When these prices were first proven, they were competitive with conventional fuels and attracted keen interest from investors around the world. Joules had ambitious plans to market his technology to build several commercial factories in several locations around the world. However, investors later withdrew and caused joule's plan to be collapsed during the years 1717-18, but developers believe that this technology should continue to evolve.

There are also exciting developments in the field of engineering bacteria and enzymes related to carbon dioxide reactions. Scientists at the University of Dundee (UK) recently developed a process that enables E. coli (E. coli) to act as a way to capture active carbon and convert carbon dioxide into formic acid [37]. American scientists have developed a new enzyme called formula, which can convert formaldehyde to dihydroxyacetone - a reaction that is not known naturally using a computational protein design program. This allows the unique carbon dioxide fixation pathway to be fed directly into the central metabolism of E. coli. Strains that cross this path can be modified to convert carbon dioxide into fuel, such as ethanol. Although still in its early stages of development, this approach paves the way for alternative CO_2 conversion paths using microbial biotechnology.

Carbon dioxide polymerization

Polymers are traditionally derived from petrochemicals. CO_2 ring polymerization and epoxides were discovered to synthesize a wide range of aliphatic polycarbonate in the 1960s and are now used to produce and apply a practical scale. Asahi Kasei (Japan) (and therefore non-corrosive) has developed a process to produce polycarbonate from carbon dioxide without the use of toxic phosgene and CH_2Cl_2 [39]. The process uses ethylene oxide, bypassing its carbon dioxide, and bisphenol-A as a raw material to produce two essential products: polycarbonate and ethylene glycol. The catalysts are very selective, which leads to high purity and high productivity, thus separating and purifying the product is unnecessary. There is also no waste to dispose of or treat. The developers claim that the Asahi Kasei process has lower capital costs than the traditional phosgene process [39]. Since the first commercial polycarbonate production started in Taiwan (China) in 2002, many Asahi Cassis processing plants have been in South Korea, Russia, and Saudi Arabia under license or construction. Asahi Kassi sold the processing license to six companies by 2019 with a polycarbonate production capacity of 1.07 t/m annually, which means 0.185 metric tons of carbon dioxide per year can be installed in products [40],[41].

In the Dreams production project, Covestro (Germany) and its partners developed a process that uses up to 20% carbon dioxide as raw materials for the use of polyethylene carbonate (Cardyon polyli polyols). The catalyst created for this process is very selective and thus prevents the formation of unwanted by-products. Also, polygon cardy has the properties required to use polyurethane foam [1]. Since June 2016, Covestro has been manufacturing a factory in Dormagen, Germany, to manufacture flexible Cardin for polyurethane foam for use in mattresses and upholstery furniture. The plant has a capacity of 5,000 tons annually, and the carbon dioxide is treated from the waste product from a nearby chemical facility [42].

Neommer (USA) has developed a catalytic process to produce polypropylene carbonate granules that contain up to 50% of the weight of carbon dioxide. Its trademark is Converge® Polymers, primarily in polyurethane formulations used in coatings, adhesives, sealants, elastomers, and rigid foams. The company's core products (1000 and 2000 molecular weight) are manufactured in a multi-ton commercial complex in Houston (USA). Neumer claims that the combination of these new polyols in existing formulations improves the final product with the appropriate performance, strength, and air. At the cost of less than 200 $ per day/tonne, carbon dioxide is cheaper than conventional petroleum raw materials, so Converge® granules are less expensive than conventional pellets if produced commercially [1, 43]. In November 2014, Neommer announced that Jowat AG, a German-based industrial adhesives supplier, would be the first to commercially adopt new Converge® Neommer polymers for use in polyurethane hot melt adhesives. In 2016, Neommer announced that it had completed commercial-grade solid foam experiments with two unique pellet cells. Both polyol mixtures were treated in extensive continuous packaging lines, and by combining polyols Converge® with recycled polyethylene terephthalate (r-PET), improved polyol formulations allow foam manufacturers to produce polyisocyanate foams and all materials using conventional processing equipment and conditions. Reducing the costs of petrochemicals and polishing. In 2016, American auto company Ford announced that it had developed and tested new components and plastics for applications such as seat cushions, using Converge® carbon dioxide granules captured during its operation [44].

Some other companies and organizations actively produce CO_2-based polymers. In China, low-tech technology Yangtze Zhangjiang Tianguan says it has developed a catalytic-polymerization system for propylene oxide and CO_2 (a by-product of the ethanol production process) to produce biodegradable polypropylene carbonate. In 2015, the production capacity was 25,000 tons annually, and new facilities of 100,000 tons annually were under construction [45]. Other Chinese manufacturers of CO_2-based polymers include Jinlong Green Green Chemical Co, which uses the aliphatic polyethylene polymers for carbon dioxide and ethylene oxide using a metal-reinforced compound polymer as a catalyst and biodegradable polyurethane foam and the local company of Mengxi components from Inner Mongolia Polypropylene R/R using CO_2 from cement kilns [46], [47].

Newlight Technologies (USA) has developed a biological system to produce brand-name plastic materials called AirCarbon [48]. The process consists of three steps: capture, extraction, and polymerization. First, the concentrated release of methane or carbon dioxide from the sources is directed to the biological control reactor. This carbon release is combined with the Newlight bio-catalyst, which removes carbon from methane or carbon dioxide. Ultimately, carbon, oxygen, and hydrogen are regenerated into a long-chain biologically biodegradable thermal polymer. AirCarbon consists of about 40 percent of the weight of oxygen from the air and 60 percent of the weight of carbon and hydrogen from the released carbon sequestration. It is a high-performance thermoplastic and can be used as a substitute for oil-based plastics. Developers claim that Independent Life Cycle Analysis (LCA) has confirmed that AirCarbon is a carbon-negative (net harmful CO_2 emissions prevention). Besides, AirCarbon is cheaper than its oil-based counterparts due to its highly efficient Biostimulant produced by Newlight Technologies [48].

AirCarbon's manufacturing process reached a commercial scale in 2013 and is currently being used for packaging by companies such as Dell and Body Shop. In July 2015, Newlight Technologies signed a 20-year overseas contract with Vinmar International Limited, a key player in the global petrochemical industry, to sell 100% AirCarbon PHA (Polyhydroxyalkanoates) from the planned 2250 Newlight production facility. The contract also covers 100% of the production of two AirCarbon production plants with a total of more than 8.6 tons over 20 years. Newlight Technologies also signed a 5.4 tonnes production license agreement with IKEA in 2016 and a 15-year production license agreement with BV Paques Holdings [48].

Economic Technologies (UK) has developed two homogeneous catalyst systems: alternating catalyst systems and adjustable catalyst systems [49, 50]. Alternative catalyst systems enable the polymerization of epoxides and carbon dioxide to produce polycarbonate granules with as much CO_2 capture as possible (see Figure 12). These polyols have excellent properties for some high-performance applications, but they use a higher viscosity than their traditional petrochemical counterparts, which limits their use elsewhere. Adjustable catalyst systems overcome this limitation by allowing the amount of carbon dioxide in the pellets to meet program performance requirements. For making polyurethane, PEs interact with diisocyanates, which can be used for a variety of applications, including mattress or car foam and paint-resistant coatings. Developers claim that both catalyst systems can work efficiently in polymer production plants without creating valuable by-products [49]. Experiments with the carbon dioxide taken from the UK's first CCS pilot project at the Vered Power Station showed that the catalysts were strong enough to withstand impurities in carbon dioxide, resulting in the same polymer resulting from the use. Pure CO_2 Econic Technologies recently integrated a display plant that combines all elements of the industrial production process, from reaction to final product use [50].

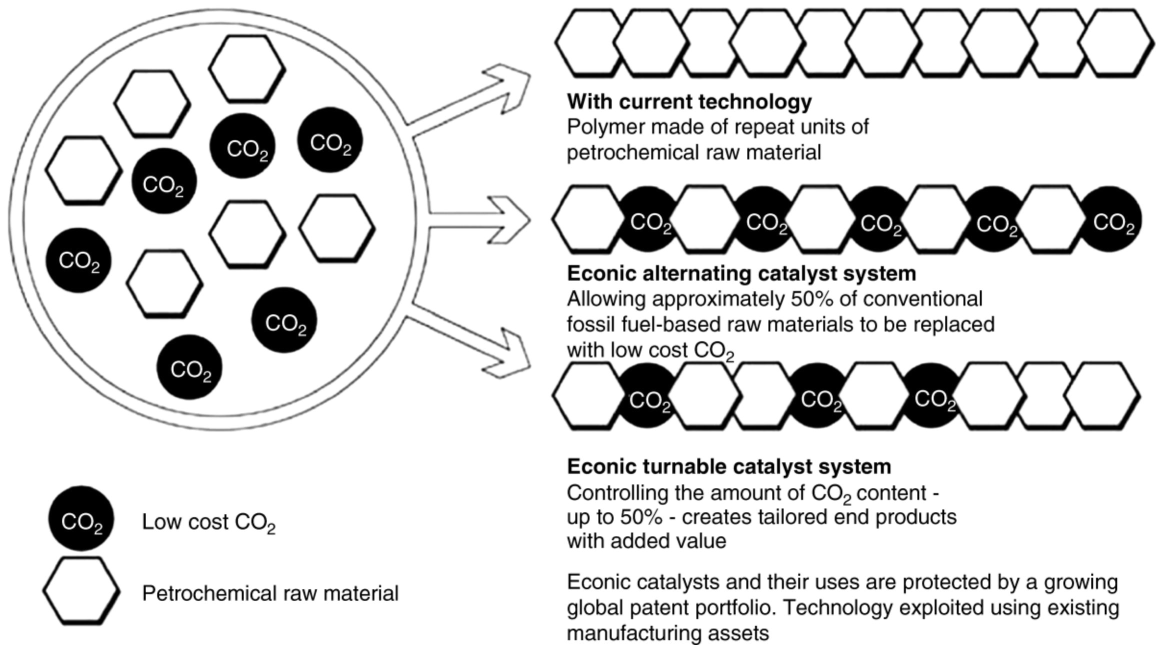

Figure 11. CO_2 polymerization techniques [51]

CO_2 polymerization techniques are evolving rapidly. Some companies have been marketing carbon dioxide-based polymers for years, while others have been marketing their oil-based products. Carbon dioxide-based polymer products can be expected to appear in the commercial market shortly.

Mineral carbonation

The CO_2 concrete refining process, developed by CarbonCure Technologies (Canada), stimulates the liquid CO_2 to be compressed into the mixture in wet concrete during mixing [8]. Carbon dioxide is sintered under atmospheric pressure without the need for individual baking chambers. Concrete products have the same or better quality than conventional products. Baking time is significantly reduced, and costs are reduced. However, cost savings with CO_2 for the baking process are partially offset. After injection, the carbon dioxide is chemically converted to solid metal and permanently stored in the concrete. It is estimated that the efficiency of CO2 absorption in concrete is about 50-80%. One cubic meter of concrete can carry up to about 3.5 kg of carbon dioxide [8,5]. Preliminary analysis shows that CO_2 sintering is less expensive than using a non-chlorine accelerator [52]. This process can be adapted to the concrete assembly system and does not affect average performance. The CarbonCure process has already been implemented in several prefabricated concrete plants owned by several manufacturers with 25 building factories and 45 mixing plants, mainly in North America, and there are plans to strengthen them further. [53]. In January 2018, CarbonCure announced that it had cooperated with five companies to demonstrate their technology to convert carbon dioxide emissions from cement production to value-added concrete for construction projects. Carbon dioxide emissions will be captured from the Argus Roberta Cement plant near Calra, Alabama (USA), transported and reused in the Argus Glenwood process equipped with the CarbonCure process. The captured CO_2 concrete is then used in a local construction project [53]. CarbonCure is one of 10 NRG COSIA Carbon XPRIZE Finals.

Solidia Technologies (USA) is currently marketing concrete and cement manufacturing technology. During the actual refining process at Solidia Technologies, the finished concrete is poured into molds and vibrations to obtain the strength of the concrete. The raw concrete is then removed from the mold and loaded into the baking room. Carbon dioxide is injected into the cooking system, which closes until the cooking process is complete [51]. The developer claims that these technologies can reduce production and reduce costs by improving the performance of cement and concrete while reducing the carbon footprint of Solidia concrete by 70% and water consumption by 60-80%. It is estimated that up to 300 kg of carbon dioxide can be absorbed per ton of Solidia Cement cement used in the construction of concrete. Solidia formwork when using manufacturers' assembly/mixing equipment meets a wide range of concrete formulations, methods, and standards. Concrete reaches full strength in 24 hours compared to the maximum of 28 days required for conventional concrete products [52]. Solidia Technologies is now marketing its technologies.

In 2012, Carbon8 Systems (UK) succeeded in marketing its patented technology for carbon filtration (ACT) to produce carbon-negative materials. ACT uses CO_2 to treat a wide range of thermal waste such as cement dust, steel slag, shale ash, fumigation, or paper ash, and contaminated soil [44, 51]. ACT Shows. The waste is mixed with precisely controlled quantities of liquid carbon dioxide and water in the carbonization pre-treatment mixer. The gaseous waste is sent to the batch mixer, where fillings and folders are added. The mixture is then sent to the granules, where carbon dioxide is injected into the gas to accelerate the cement process to form a circular aggregate. Screening and storing materials complete the process [33]. Rainwater is collected and used in the process, and no solid, liquid, or gaseous waste is discharged. This is a thermal reaction and, therefore, does not require heat. Electricity is used only for the transportation of materials through the system. As a result, the process removes more carbon dioxide than the total emitted carbon dioxide, and it is considered as a carbon-negative process.

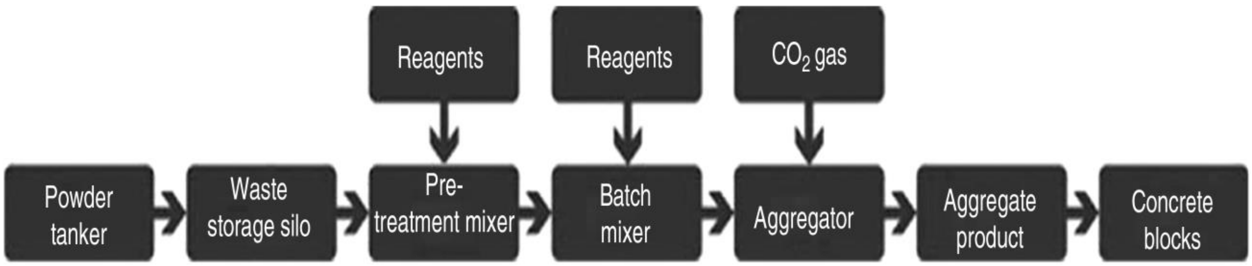

Figure 12. ACT Carbon8 Systems [29]

The first ACT plant at Brandon in Suffolk (UK) was operational in early 2012, and now over 65,000 tonnes per year of light gas grains (or 30,000 tonnes APCR) of MSW air pollution control residue is produced. The end product derived from the hazardous APCR was identified by the British Environment Agency as "the end of waste." In February 2016, a second 100,000 ton per year plant was established in Avonmouth, and three other factories in the UK of the same size or larger are expected by 2020 [25, 48].

UCLA team researchers (University of California, Los Angeles, USA) are working on a unique carbon process that converts CO_2 emissions from power plants and industrial plants to an almost neutral building material called CO2NCRETE. Their approach is to integrate many technologies into a closed-loop process, to use flue gas extracted from point source transformers by efficiently restoring wasted heat and enriching carbon dioxide in the gas stream to produce CO2NCRETE. The $CaOH_2$ calcium hydroxide binder system is mixed with materials and additives to form a CO2NCRETE building element in the desired shape. The final and critical step is to merge the captured carbon dioxide with the CO2NCRETE element through a carbonate reaction to form a substantial building component. As a building material, CO2NCRETE is suitable for different formulations and can be manufactured in various shapes. These elements, such as Legos, can be used for the rapid assembly of buildings, bridges, and other infrastructure traditionally made using concrete [51]. The process of carbon sequestration causes carbon dioxide to be captured and converted to its source by the flue gas from power plants and industrial plants. It can transport flue gas from different sources containing different concentrations of carbon dioxide without the need for pre-treatment [7]. The UCLA Carbon Upcycling team is one of the other finalists in NRG COSIA Carbon XPRIZE.

Curbstone Innovation NV Belgium and the Canadian company CarbiCrete independently produced a cement-free concrete manufacturing process using carbon dioxide with steel slag [60]. The Curbstone process uses an innovative grinder to crush large slag into fine particles used as fillers. The mixers mix different raw materials (fillers and different slag sand) with water. The granularity of raw materials and the amount of water is precisely controlled for the optimal carbon process. Next, the wet mixture is hydraulically pressed to the desired shape, such as a large brick, which may be hollow or solid. Carbonization in autoclaves is carried out under high pressure and temperature [11]. The carbon activation process developed by CarbiCrete uses stainless steel slag to replace cement, and carbon dioxide is injected into the wet concrete of carbonization and hardening. This process can be performed in any concrete manufacturing plant, almost without any interruption in the process. CarbiCrete estimates that producing a standard-size concrete block (often referred to as an 18 kg cylindrical block) will save 2 $kgCO_2$ and 1 $kgCO_2$ during the process using this process [17].

The carbon dioxide mineral processes for producing inorganic chemicals have also been studied. The SkyMine [21] process, produced by Carbonfree Chemicals (formerly Skyonic), absorbs and uses carbon dioxide. This process can remove CO_2 and acid gases like SO_2 and NO_x as well as heavy metals from exhaust gases of the power plants and other industrial plants and convert them into marketable products like sodium bicarbonate or sweet weld, water hydrochloride solution. Convert sodium hydroxide. Alternatively, caustic soda or bleaches use an electrochemical method to prepare a low concentration of NaOH with salt and water. The solution is then used for crushing carbon dioxide and other chemicals into the flue gas and can ultimately produce highly pure $NaHCO_3$. Electrolysis also produces hydrogen and chlorine gases. The SkyMine patent process can be applied to new and existing fixed emissions sources such as refineries, power plants, and steelworks. The first SkyMine facility was built at the Capitol Aggregates cement plant in San Antonio, Texas (USA), and commissioned in March 2015. It is estimated that the plant will produce a 15 percent reduction in carbon dioxide emissions, which is equivalent to annual savings of 83,000 tons of carbon dioxide [19].

Life cycle assessment

The CCU, carbon dioxide savings, is mostly dependent on the option used. To assess and estimate the full range of benefits such as avoided net carbon dioxide emissions, the length of time that carbon dioxide is stored in the product, and the potential market value of the use, the use of acoustic analytical methods is essential [11], [15]. The LCA covers the entire life cycle of products and processes from raw material extraction and transportation through the production and use of product recycling and final disposal [19]. However, many CCU technologies are being developed, and data is not yet available for a full cycle evaluation. However, many LCAs have been assumed for different CCU operations. These results may not be accurate and reliable, but they can provide comparisons of scores [21].

Using the data provided by Joule Technologies, an analysis of the United States Environmental Protection Agency found that sunflower Joule Technologies, bioethanol from carbon dioxide (as described in sections before), can be compared with systems fueled by fossil fuels [33]. Cuellar Franca and Azabagic [29] compared 16 studies of life-cycle assessment studies in different CCU methods published in the recent literature. They recalculated some results for comparison purposes, as shown in Figure 15. 13 of these plants use fossil energy plants as a source of carbon dioxide, and the rest use carbon dioxide from chemical plants such as ammonia and hydrogen production. The results indicate that the carbonate of minerals can reduce global warming (GWP) by 4-48% compared to the lack of CCU [44]. This method is estimated to improve the carbon recycle from 524 kg of carbon dioxide equivalent per ton of carbon dioxide removed directly from the factory to 1073 kg of carbon dioxide when CO_2 is captured using monoethanolamine (MEA) [18]. By using carbon dioxide to produce chemicals, in particular, dimethyl carbonate can reduce carbon emission by 4.3 times compared to the conventional dimethyl phosgene process (31 instead of 132 kg of carbon dioxide/equivalent/dimethyl carbonate). CO_2-EOR has 2.3 times less than emission to the atmosphere. Carbon dioxide absorption by microalgae for GWP biodiesel production was 2.5 times higher than fossil diesel production [19].

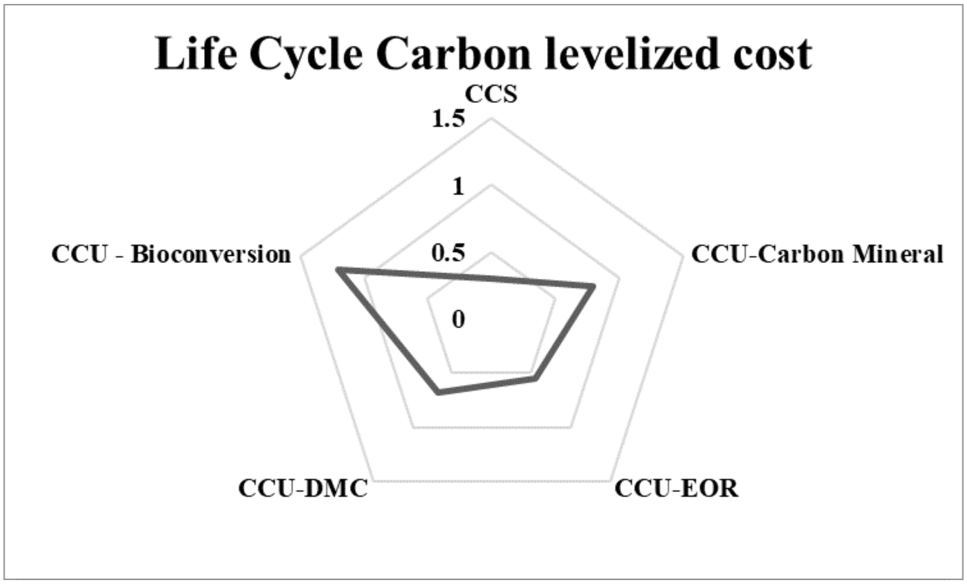

Figure 13. GWP comparison of different CCU options [64]

Cradle-to-gate analysis (including production and all upstream operations) The polyols are analyzed to produce polyurethane using carbon dioxide (taken from Lignite plant) using data from a real industrial test plant [15]. The analysis showed that the production of polyols with 20% CO_2 in the polymer chains resulted in saving 3 kg of CO_2-eq emissions per kg of CO_2[19]. The use of fossil fuels can be reduced by 16%, and emissions of other air pollutants can also be reduced [10].

conclusions

Using carbon dioxide as the feedstock to produce a wide range of chemicals and materials is a challenge, but it provides new opportunities for diverse industries. CCU covers a range of technologies and products and covers a wide range of players and new industries. Various technological paths have been explored. In recent years, CCU technologies have made rapid progress. Numerous technologies to produce fuel or chemicals with catalytic, electrochemical, and biocompatible-CO_2 or CO_2-polymers through CO_2 polymerization are currently in the commercial phase, and there is more in the commercial market. At the heart of all these technologies is a catalyst that converts CO_2. Intensive research and development are in the process around the world. Several catalysts (and microbes) have been designed and tested, and have demonstrated the ability to convert carbon dioxide into various highly efficient, selective, and efficient chemicals. Most research is still in the early stages of development, and more work is needed to develop technically and economically feasible processes for converting carbon dioxide into fuel and chemicals on a commercial scale.

Technological developments in the manufacture of building materials and others through carbon dioxide carbonate such as concrete impregnated with carbon dioxide and accelerated carbonation of waste to produce more advanced materials, and many processes were marketed. These technologies are easily installed or modified in existing production systems and are economically competitive at relatively low costs. Manufactured products of similar quality or better than those traditionally produced and can permanently store carbon dioxide. Therefore, it is expected to be one of the first CCU technologies to achieve widespread.

The LCA of CCU operations shows that CO_2-derived polymers and CO_2-saturated polymers have better environmental performance and lower carbon footprint than their conventional counterparts. The LCA also shows that fuels such as methanol from carbon dioxide use environmental benefits when using renewable energy to produce them.

Looking ahead, the CCU will continue to grow in short to medium term, especially in more technologically advanced areas, such as polymers derived from carbon dioxide, and methanol production. In the long run, CCU becomes a vital component of the circular carbon economy with low carbon production and low sustainable chemicals.

Acknowledgments

I am at this moment to acknowledge the scientific supports of the Amirkabir university of technology.

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HOW TO CITE THIS ARTICLE

Nima Norouzi, Saeideh Choubanpishehzafar "**An Overview on the Carbon Utilization Technologies with an approach to the negative emission construction material**" International Journal of New Chemistry., 2021; DOI: 10.22034/ijnc.2021.123020.1102.