



Research Article

Analyzing challenges to maximize the efficiency of industrial processes using carbon capture and hydrogen energy production from methane

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ABSTRACT

Greenhouse gases (GHGs) significantly impact on our environment, negatively affecting living conditions. Therefore, we strive to harness these GHGs for humanity's benefit. Carbon dioxide is viewed as a valuable resource for generating new products, including concrete treatments and chemicals. In the food industry, carbon dioxide is used for enzyme inhibition, protein precipitation, maintaining food quality, and also being used in the soft drink sector. This paper presents a novel approach to utilizing greenhouse gas emissions for beneficial purposes. Methane and carbon dioxide are two primary gases contributing to climate change, which present significant environmental, social, and economic challenges. We also aim to explore enhancing industrial operations by implementing advanced carbon capture technologies and leveraging methane as a source for hydrogen production. Focusing on these two key areas can significantly reduce emissions and promote sustainable energy practices. By addressing the research gaps, it is possible to analyze most of the challenges in order to significantly enhance the efficiency and sustainability of industrial processes, contributing to a low-carbon future while supporting research and development for future applications of CO₂ that could contribute to a CO₂-neutral economy. And this may have a massive impact on the carbon markets as carbon credits are emerging globally. A legislative and regulatory framework for trading hydrogen and carbon in various new uses and applications should be established. In this paper, different methods for producing hydrogen from methane have proven an energy efficiency of 65% to 75%. Other methane applications are still in the experimental phase with an estimated energy efficiency of about 58%, marking a significant advancement in the production of clean hydrogen and solid carbon for various applications, all while generating minimal emissions.

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INTRODUCTION

A Brief History of Efforts to Reduce Carbon Dioxide and Methane Emissions

The recognition of the need to address greenhouse gas emissions, primarily carbon dioxide (CO₂) and methane (CH₄), is a relatively recent development, dating back to the mid-20th century. However, significant efforts to mitigate these emissions have gained momentum over the past few decades, driven by growing scientific evidence of climate change and its potential impacts, as shown in Figure 1 [1]:

❖ Early awareness and initial actions [2]:

- 1950s and 1960s: Scientists began to understand the greenhouse effect and the potential role of human activities in altering the Earth's climate. Scientists such as Roger Revelle and Hans Suess released the revolutionary findings of the growing amount of CO₂ in the atmosphere because of the burning of fossil fuel.
- 1970s: A turning point came in 1979 as the first international conference on climate change was held. Instead, the conference was acknowledged in the risks of climate change and the need to further study the issue and collaborate internationally.

❖ International cooperation and climate treaties [3]:

- 1980s: Intergovernmental panel on climate change (IPCC) was formed in 1988 to evaluate the science of climate change. The reports by the IPCC have furnished very important evidence that can guide the policy makers and other individuals on the dangers of climate change.
- 1990s: The framework convention on climate change of the United Nations (UNFCCC) was adopted in

1992 and it paved way to global action on climate change. The Kyoto Protocol was signed up in 1997 and it enacted legally binding emissions reduction objectives to the developed countries.

- 2000s: An important step was made in 2015 with the Paris Agreement. It seeks to reduce global warming by at least two degrees Celsius (or less) beyond the pre-industrial levels and pursue an aim of reduction of at least 1.5 degrees Celsius.¹ The agreement introduced the principle of Nationally Determined Contributions (NDCs) whereby the countries establish their emission reduction targets.
- 2010s and 2020s: Over the past several years, attention to the contribution of methane emissions to climate change has grown. Bridging the gap between Global warming and the effects of global warming, the Global Methane Pledge was introduced in 2021, destination being to lower the total amount of methane emission on the planet by 30 percent by 2030, as illustrated in Figure 2.

It is worth mentioning that the history of the struggle to decrease emission of greenhouse gases has not finished yet. The rest of the world is striving to achieve sustainable future as the scientific community deepens their understanding on climate change and the world is opening up to more technological developments.

Greenhouse gases (GHGs) trap heat in the atmosphere of the earth. The ultraviolet radiation of the sun heats up the surface of the earth during the day which cools down and emits heat back to the atmosphere when it is dark. But, greenhouse gases cause some of that heat to be trapped. One of these greenhouse gasses is carbon dioxide (CO₂); the gas is not flammable and is colorless at standard temperature and pressure. Carbon dioxide is far less prevalent in the environment of the Earth in comparison to nitrogen and oxygen but it is important in controlling climate on our planet. The release of carbons into the atmosphere

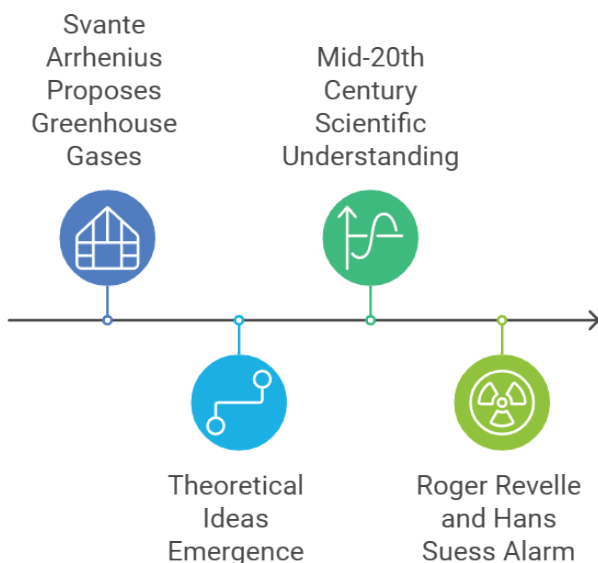


Figure 1. Evolution of climate change awareness.

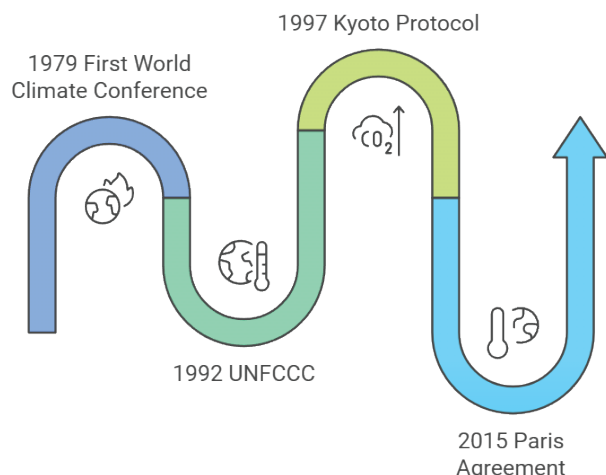


Figure 2. Key milestones in global climate agreements.

due to human activities is increasing and this is caused by the burning of fossil fuels, the increase in industrial establishment, and deforestation. It can take hundreds of years to dissipate and unlike other green house gases, this gas helps in fueling climate change by trapping heat stored within the solar radiation. At this point, one of the recent projects and an effective method to reduce climate change impacts is carbon capture. It particularly focuses on significant contributors to the emissions e.g., power plants and energy-intensive industries [4].

Three common ways of capturing carbon are available, post-combustion systems, oxy-fuel combustion systems and pre-combustion systems. The extracted carbon could be further stored in underground geologic storage sites or be recycled to produce new products and uses, including cement, chemicals, food, and drinks. The risks, tracking, and the legal issues of CO₂ capture projects are not new because these areas are included in the existing health, safety and environmental monitoring actions in this industry. But these projects are unprofitable to the companies and stakeholders at this time. As such, it is important to put up a binding legal and regulatory system among these parties. Figure 3 illustrates the carbon dioxide capture cycle that comprises of emission sources, channels of capture, storage or reuse, and monitoring and regulations [5].

Conversely, hydrogen is another clean type of energy to be produced and it is the most common chemical element with an estimated 75 percent universe mass. There are very large numbers of hydrogen atoms in water, plants, animals and humans on planet Earth. The most important benefit of hydrogen is that hydrogen burns up with oxygen and gives no CO₂ reaction because hydrogen has no carbon atom in the hydrogen molecule. When the pure oxygen is burnt with hydrogen, the pure water is the only product that is formed [6].

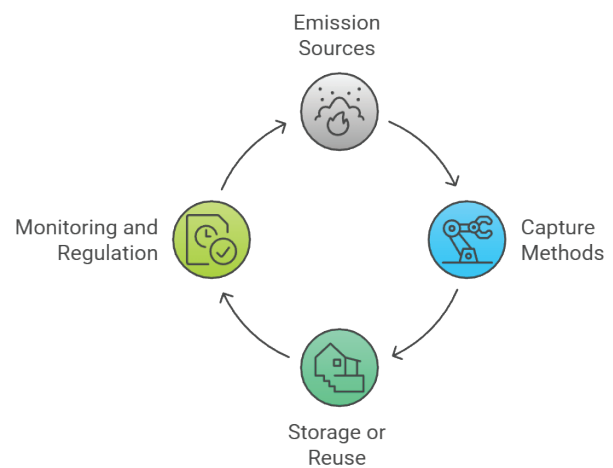


Figure 3. Carbon dioxide capture cycle.

Extraction of hydrogen needs energy and the energy requirement is different and depends on the production process. This process is dependent on the amount of hydrogen that can be derived out of an energy source, determining its efficiency. This efficiency ought to be maximized ideally to make the energy originating the source efficiently converted to a form of hydrogen as an energy carrier. There are various resources that can be used to produce hydrogen. Today, hydrogen is produced primarily based on fossil fuels, especially, natural gas, by means of chemical reactions, among which are steam methane reforming (SMR), auto-thermal reforming (ATR), and methane pyrolysis. Also, hydrogen can be produced with electricity (again either using supplies of renewable energy, such as wind, sun, geothermal, and biomass, or fed by the grid, as illustrated in Figure 4) [7].

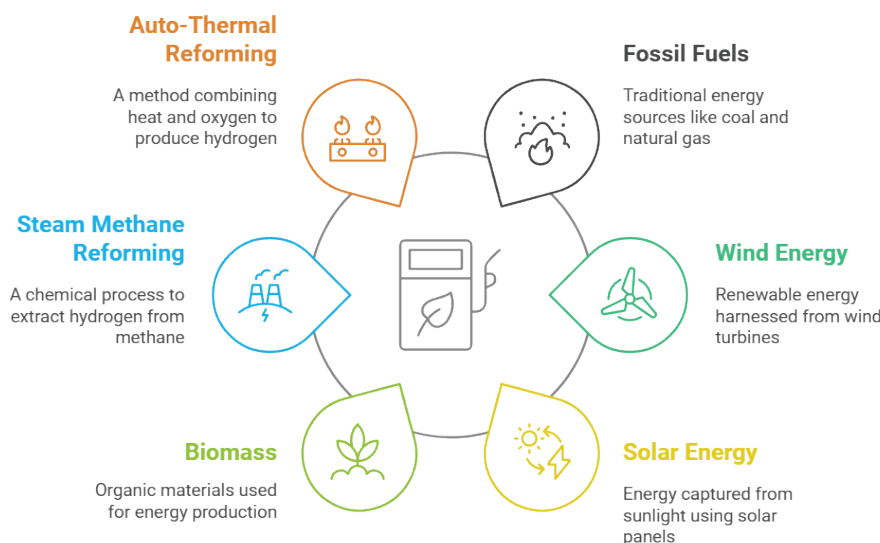


Figure 4. Hydrogen production from different resources.

When talking about carbon and hydrogen, it becomes impossible not to mention such a powerful greenhouse gas as methane, which does not exist in the environment long enough. Methane has an average atmospheric lifetime of approximately 12 years; this is a short period compared to hundreds of years that it takes carbon dioxide to exit the atmosphere. This implies that cutting down the number of methane cases may be a simple and effective measure of curbing part of the climate change in a matter of several decades. Agriculture, oil and gas, landfills, wastewater management, and a number of different industrial processes are the primary contributors to methane emissions [6]. Figure 5 shows how the ability to capture the CO₂ and CH₄ can be useful in reducing climate change via positive pathways, including the storage or re-use of CO₂ and the separation of methane to create alternative products.

The Sustainable Development Goals (SDG) are meant to reduce the effects of climate change and environmental degradation. This can be done by capturing the methane emissions and converting them into both carbon and hydrogen. This does not only improve the efficiency of energy consumed in industrial activities but also it makes it

possible to develop new goods and services that bring into support the principle of the closed-loop. A more in-depth discussion of this will follow in this paper.

CARBON CAPTURE, HYDROGEN AND METHANE

We examine and discuss several methods of capturing carbon based on carbon dioxide and methane in this paper. We aim to discover the possibilities of using carbon in the industrial processes and harvesting the hydrogen that is extracted from the methane and used in other industries, energy production and in energy saving activities. We will start by defining carbon capture, hydrogen and methane.

Carbon Capture

Carbon capture refers to a collection of technologies that capture carbon dioxide (CO₂) emissions from industrial processes and power plants, preventing them from staying in the atmosphere. As shown in Figure 6, the captured CO₂ can then be either utilized for various purposes or stored permanently undergrounds [8].

The different CO₂ capture methods (introduced in Figure 7) are:

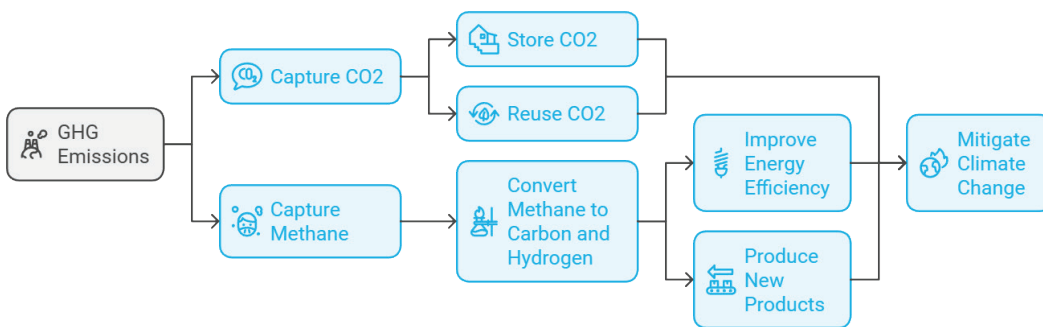


Figure 5. Mitigation pathway from capturing CO₂ & CH₄.

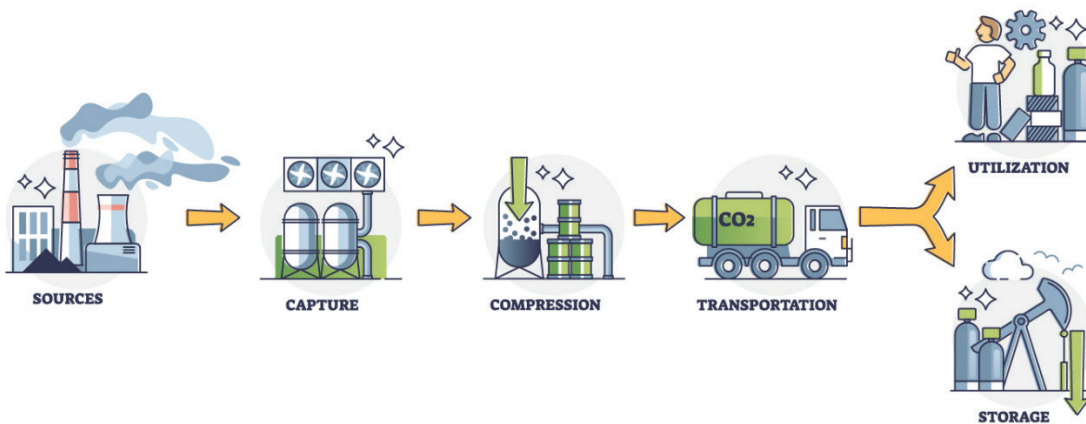


Figure 6. Carbon capture concept.

1. Carbon Capture and Utilization /Storage (CCUS/CCS)
2. Carbon Capture at Power Plants
3. Direct Air Capture (DAC)
4. Enhanced Rock Weathering (ERW)
5. Aqueous Amine-Based CO₂ Capture
6. Membrane Gas Separation
7. Carbon Capture and Conversion
8. Bioenergy with Carbon Capture and Storage (BECCS)
9. Chemical Looping
10. Cryogenic Carbon Capture (CCC)
11. Carbon Capture Using Nanotechnology

Table 1 below shows a comparison of various CO₂ capture technologies with their description, advantages, and challenges [8-12].

The process of CO₂ capture technologies is complicated, and can frequently be misconstrued as a step to a more sustainable future. Although these technologies cannot be used as an excuse to carry on consuming fossil fuels, they are very important in curbing emissions in a manner that cannot be achieved by other technologies. More efficient alternatives exist in most situations (such renewable energy sources in the power sector), but in some areas of industry and at the system level (to offset emissions), capturing and trapping CO₂ is critical.

In order to capture CO₂, a separation of carbon dioxide by a number of physical and chemical techniques, which include: absorption, adsorption and membrane technology, are used. Alternative methods of capturing carbon

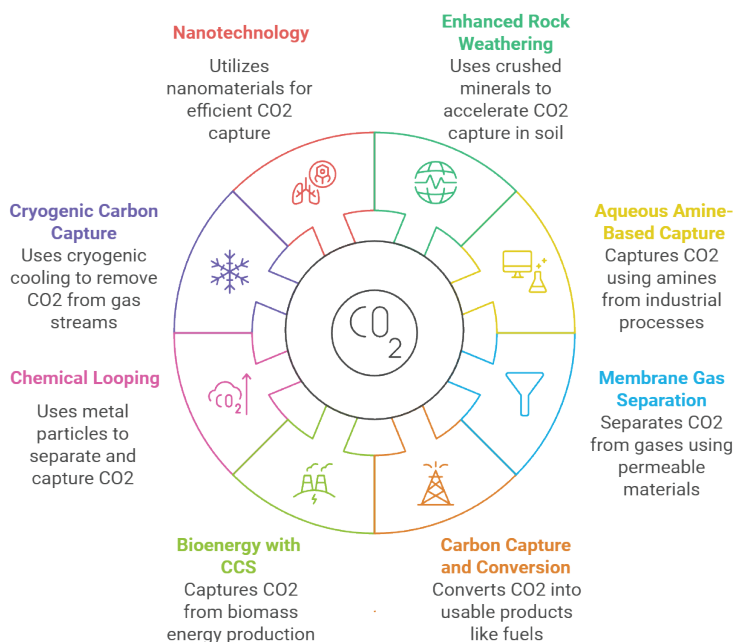


Figure 7. Carbon capture technologies.

Table 1. Comparison of CO₂ Capture Technologies [created by author]

No.	Capture Technology	Description	Advantages	Challenges
1	Carbon Capture and Utilisation /Storage (CCUS/CCS)	It is a set of technologies that capture carbon dioxide (CO ₂) emissions from industrial processes and either stores it underground or utilize it for other purposes.	<ul style="list-style-type: none"> ▪ Mitigation of Climate Change ▪ Enhanced Oil Recovery (EOR) ▪ Production of Synthetic Fuels ▪ Industrial Raw Material 	<ul style="list-style-type: none"> ▪ High Cost ▪ Energy Intensive ▪ Leakage Problem ▪ Public Perception Issues
2	Carbon Capture at Power Plants (CCPP)	It is a technology designed for the removal of carbon dioxide (CO ₂) emissions by fossil-fuel power plants..	<ul style="list-style-type: none"> ▪ Low Greenhouse Gas Emissions ▪ Increased Operational Lifetime of Power ▪ Capacity to Generate Negative Emissions 	<ul style="list-style-type: none"> ▪ High Energy Intake ▪ High Operating Expenses ▪ Technological Complexity ▪ CO₂ Storage and Transport

Table 1. Comparison of CO₂ Capture Technologies [created by author] (continued)

No.	Capture Technology	Description	Advantages	Challenges
3	Direct Air Capture (DAC)	The technology involved here entails capturing carbon dioxide (CO ₂) emissions directly from the atmosphere. The technology involves the intake of air, CO ₂ filtration, and its subsequent storage underground or utilization.	<ul style="list-style-type: none"> ▪ Carbon Negative Emissions ▪ Global Implementation Capacity ▪ Potential for CO₂ Utilization 	<ul style="list-style-type: none"> ▪ High Energy Requirement ▪ High Cost ▪ Limited Capacity ▪ CO₂ Storage and Transport
4	Enhanced Rock Weathering (ERW)	The method involved here entails enhancing the rate of rock weathering to remove CO ₂ emissions from the atmosphere through a natural process. This process entails the crushing of rocks, which is subsequently scattered on the ground to enhance exposure to atmospheric CO ₂ .	<ul style="list-style-type: none"> ▪ Natural Process ▪ Long-Term Storage ▪ Soil Fertility 	<ul style="list-style-type: none"> ▪ Large Scale Land Requirements ▪ Limited Capacity ▪ Environmental Impacts of Massive Rock Crushing and Transport
5	Aqueous Amine-Based CO ₂ Capture	It is a mature technology involving the use of a liquid medium (typically aqueous amine solutions) for absorbing CO ₂ emissions from flue gases.	<ul style="list-style-type: none"> ▪ Mature Technology ▪ High CO₂ Capture Rate ▪ Flexibility 	<ul style="list-style-type: none"> ▪ High Energy Requirement ▪ Corrosion ▪ Solvent Degradation ▪ Environmental Impact of Amine Solvent
6	Membrane Gas Separation	The technology involves using semi-permeable membranes to separate gases according to their molecular weights. In carbon capture applications, the membrane technology can be used to separate CO ₂ emissions from other gases within the flue gas stream.	<ul style="list-style-type: none"> ▪ Low Energy Intake ▪ No Chemical Reagents ▪ Modularity 	<ul style="list-style-type: none"> ▪ Lower CO₂ Capture Rate ▪ Membrane Fouling ▪ Constraining Operating Conditions
7	Carbon Capture and Conversion	Consists of the capture and conversion of CO ₂ emissions to valuable products such as fuels, chemicals, or construction materials.	<ul style="list-style-type: none"> ▪ GHG Emission Reduction ▪ Value-added Products Creation 	<ul style="list-style-type: none"> ▪ High Energy Requirement ▪ Technological Maturity ▪ Economic Viability ▪ Scalability
8	Bioenergy with Carbon Capture and Storage (BECCS)	This is a technology involving the capture and storage of CO ₂ emissions from biomass combustion. In this case, the CO ₂ emissions from biomass burning to produce energy are captured and stored underground.	<ul style="list-style-type: none"> ▪ Negative Emissions ▪ Energy Production ▪ Sustainable Land Utilization 	<ul style="list-style-type: none"> ▪ Land Utilization Competition ▪ Necessity for Water Sources ▪ Sustainability Challenges
9	Chemical Looping	The technology entails an efficient and cost-effective approach to the capturing of CO ₂ emissions from power plants and industrial processes. The process involves a cyclical operation using a metal oxide (also referred to as an oxygen carrier) to move oxygen from an air reactor to a fuel reactor.	<ul style="list-style-type: none"> ▪ Automatic CO₂ Separation ▪ High Thermal Efficiency ▪ Low Environmental Impact ▪ Flexibility 	<ul style="list-style-type: none"> ▪ Oxygen Carrier Development ▪ Reactors' Design and Operation ▪ High Capital Costs
10	Cryogenic Carbon Capture (CCC)	It is a modern technology involving cooling of flue gases to cryogenic temperatures, thereby allowing the solidification of CO ₂ and separation from other gases.	<ul style="list-style-type: none"> ▪ High Efficiency of Capture ▪ Efficient Process ▪ Removal of Other Pollutants ▪ Opportunity for Product Utilization 	<ul style="list-style-type: none"> ▪ High Capital Cost ▪ High Energy Intake ▪ Complex Process ▪ Scalability
11	Carbon Capture Using Nanotechnology	Nanotechnology is employed to create advanced materials to be applied in efficient CO ₂ capture due to manipulation of materials at the nanoscale.	<ul style="list-style-type: none"> ▪ High Surface Area ▪ Selectivity ▪ Low Energy Requirement ▪ Potential for DAC 	<ul style="list-style-type: none"> ▪ Scalability ▪ Material Stability ▪ Environmental Impact Issues



Figure 8. Membrane technology applications.

dioxide through new alternative technologies are proving to be effective and membrane technology is gaining more and more appreciation. It is currently used in other industries to large-scale separate a variety of mixtures of gases. The increasing use of membrane technology is due to its low cost of operation and eco-friendliness. Gas separation using membranes is an excellent alternative to the conventional unit operations because it is relatively easy to run, economically viable, it requires little maintenance, it deals in a small space and because it consumes less energy. In gas separation, hollow fiber or spiral wound module is used and that one makes use of selective non porous membranes. Membrane gas separation is considered an alternative mechanism to the more conventional processes such as adsorption and absorption. Oxygen recovery, natural gas sweetening, recovery of hydrogen in steam and removal of carbon dioxide in methane processes using polymeric membranes are some of the applications of membrane technology (Fig. 8). Hollow fiber membranes are advantageous in that they have a good area to volume ratio, can be densely packed, and can be desired to not only withstand mechanical strength but also to be mechanically stable which as well as resistant to fouling. Moreover, hollow fiber membranes are some of the cheapest membranes in the market since they do not need supporting substance. [13].

On the other hand, adsorption is one of the most promising methods for reducing costs associated with the hold step in carbon capture. It typically has high CO₂ capture capacity, high selectivity, low-cost loot material, and adsorption capacity remained constant after several cycles.

Layered double hydroxide (LDHs) are inorganic compounds and belong to the group of two-dimensional clay minerals. They are made up of several cations (metals in the inner layers) and interlayers made of anions. the constitution of LDHs consists of metal hydroxide metals with a positive charges, like in brushite [Mg(OH)₂], and anions and water molecule that counterbalance the charges between the layers. The possibility of using LDHs in high temperature carbon capture and storage is very promising. They do not need a lot of energy to regenerate during adsorption

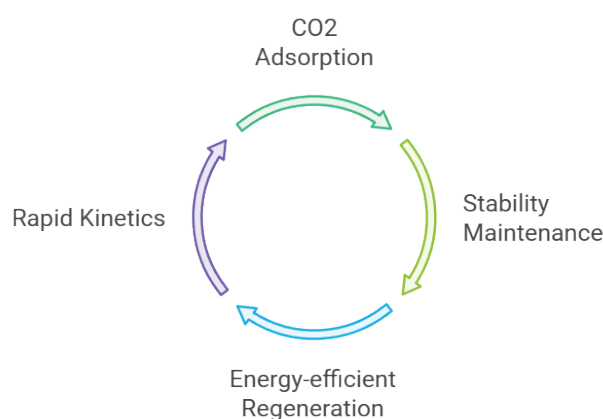


Figure 9. LDHs in carbon capture cycle.

of CO₂ and are more stable than certain solid adsorbents. Moreover, LDHs have fast adsorption and desorption kinetics, especially under the influence of water, and thus would be a promising choice to use in pre-combustion CO₂ capture processes (Fig. 9) [14].

So far, the adoption rate of CO₂ capture technologies has been slow. Though positive signals are that there are changes that are likely to take place, the industry is not beginning as a complete one. It will not be realized that these technologies will make any real difference in reducing emissions until many years down the line when capture, transport and storage infrastructure can be built [15,16].

As outlined by the net-zero emissions (NZE) scenarios of the International Energy Agency (IEA) on future stage (2050), the carbon capture and storage have a considerable potential. The aggregate ability to capture carbon dioxide (CO₂) is even estimated to rise to 1.2 gigatons (Gt) of CO₂/year by the year 2030 and beyond at 7.6 GtCO₂/year by 2050. It has been reported by Intergovernmental panel on climate change (IPCC) that a total of 15 GtCO₂ of carbon reduction will be required by the year 2050 in case average temperature increase is to be maintained at 1.5 C. Likewise, the Energy Transformation Commission (ETC) estimates

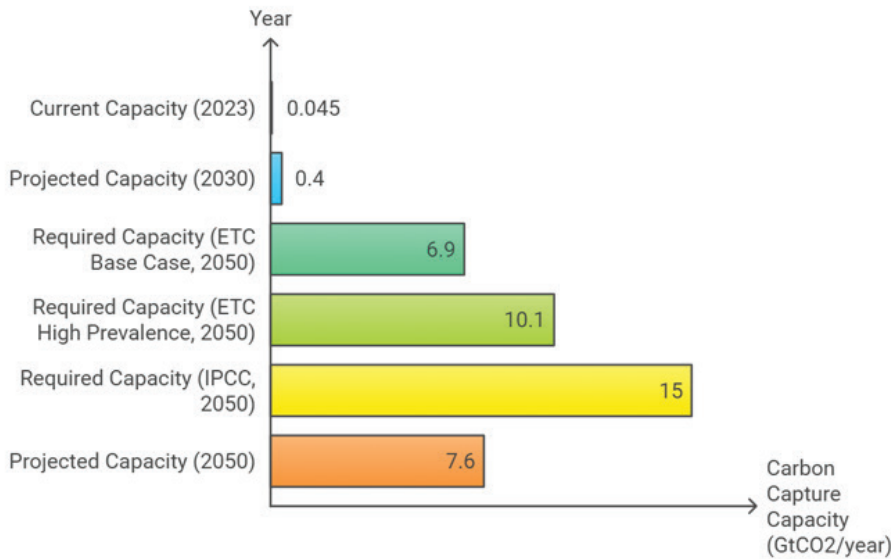


Figure 10. Carbon capture capacity and emissions reduction targets.

that up to 6.9 Gt (base case) to 10.1 Gt (high prevalence) of carbon dioxide emissions have to be captured per year to achieve net-zero by 2050 (Fig. 10). According to ref. [17], indicates the total amount of carbon that was captured in 2023 was about 45 million tons because of an IEA report. Although deployment momentum has continued to improve and approximately 200 new capture facilities have been announced as becoming operational by 2030, with all the developments, the overall annual capacity is estimated to reach almost 400 million tons of CO₂ by 2030. This is still very small against the amounts needed to achieve the net-zero goal of 2050 period [17].

The current buzzword in climate change mitigation is carbon capture and storage (CCS). The goal of CCS is to capture emissions produced during the production and processing of fuel. Nevertheless, it fails to represent the majority of the emissions, which take place down the line. Moreover, CCS consumes a lot of energy to run and therefore in the case that the energy is obtained through fossil fuels, there is a risk of increased emission. This critical review shows that in certain situations, CCS may result into a net increase in emissions. A lot of studies that seek to illustrate the possibility of CCS do not incorporate a more elaborate life cycle analysis (LCA) to cloud the actual ineffectiveness of technology. Although CCS is among the few solutions that can be employed in the reduction of emissions in sectors that are hard to decarbonize, like cement industries, renewable sources of energy are eclipsing it. Furthermore, CCS is sometimes proposed to expand fossil fuel production [18].

The operation of a CO₂ capture system reduces the overall efficiency of power generation and other processes. This leads to increased fuel requirements, more

solid waste, and greater environmental impacts compared to an equivalent facility without capture. Therefore, minimizing the energy needed for CO₂ capture and enhancing the efficiency of energy conversion processes will be key priorities for future technological development aimed at reducing environmental impact and costs. Carbon dioxide is currently separated into large industrial facilities, such as those involved in natural gas processing and ammonia production. However, these plants primarily remove carbon dioxide to meet their production requirements rather than for storage purposes. While power plants are significant sources of carbon dioxide emissions, carbon capture technology has yet to be implemented in these facilities [8].

There are three main approaches for capturing CO₂ in industrial and power plant applications (as introduced in Figure 11) [8]:

- **Post-Combustion Systems:** Captures CO₂ from flue gases after combustion. This is the most common method currently used.
- **Oxy-fuel Combustion** uses oxygen instead of air for combustion, producing flue gas that is mainly H₂O and CO₂ and is readily captured; this option is still under research and development.
- **Pre-Combustion Systems:** Captures CO₂ before combustion through gasification or oxy-fuel combustion. This method is more energy-intensive but can capture a higher percentage of CO₂.

Monitoring, risk, and legal aspects associated with CO₂ capture systems present no new challenges, as they are all elements of the industry's long-standing health, safety, and environmental control practices [8].

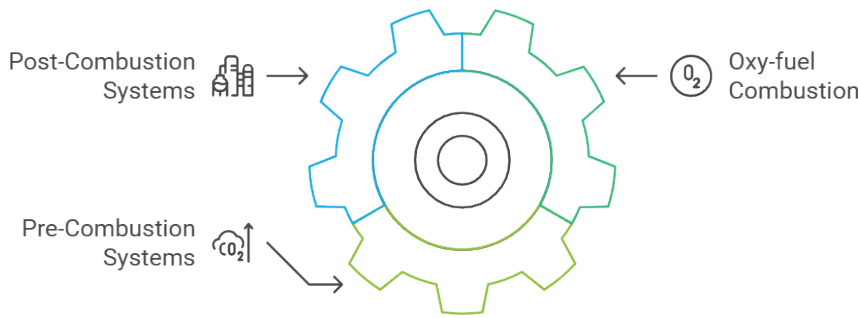


Figure 11. Carbon capture methods industrial and power plant.

Hydrogen

Hydrogen (H₂) is the most abundant element in the universe and has recently gained recognition as a crucial component of decarbonization strategies in many countries [19].

Hydrogen can be produced from both biological and non-biological sources, using various production pathways categorized by color, which indicates the type of feedstock, power source, and technique employed [20].

Hydrogen can have numerous applications, including the possibility of hydrogen being a raw material (energy storage) or a fuel source. Notably, hydrogen does not release carbon dioxide when it burns up [19].

In its normal state, hydrogen is a flammable, colorless, and odorless gas, comprising approximately 75% of the material in the universe, by mass. It is capable of holding a lot of energy and it is in its gaseous state at ambient pressure, although it can be converted to liquid at very

low temperatures -253°C. To facilitate storage, hydrogen is typically stored in cylinders under high pressure, usually at 350 or 700 bar, and in some cases up to 1,000 bar. This high-pressure storage also allows for the transportation of hydrogen in copious quantities over significant distances [21].

It’s important to note that hydrogen acts as an energy carrier rather than an energy source. The method of hydrogen production can be identified through its “color,” which corresponds to the source used. Additionally, the price of each type of hydrogen is influenced by the source and efficiency of the production technology. Often, the cost of hydrogen production is intricately linked to electricity prices [21].

The main colors of hydrogen can be explained as shown in Figure 12, but other colors, such as yellow, black, and brown, are also associated with hydrogen production [20].

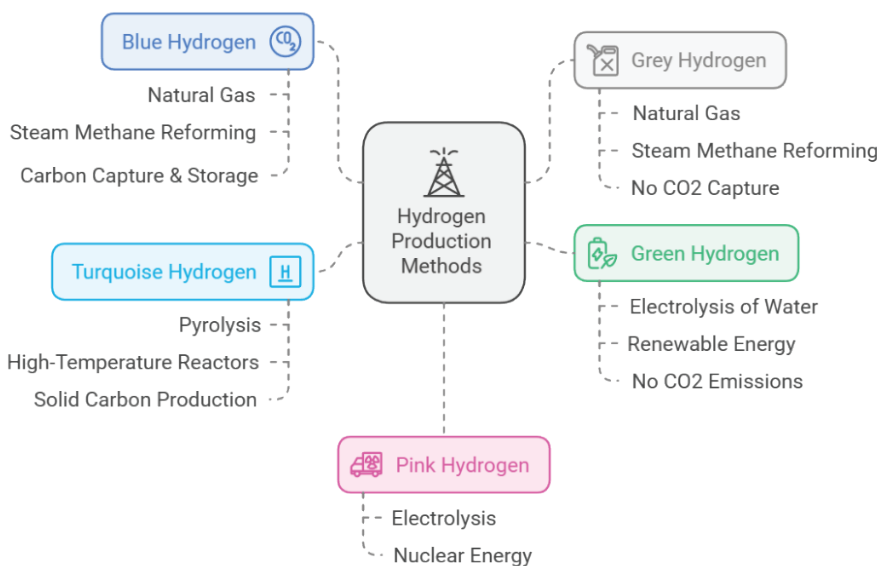


Figure 12. Main hydrogen colors production pathways.

Methane

Methane is a colorless and odorless gas that forms abundantly in nature and is also produced by certain human activities. As the simplest member of the paraffin series of hydrocarbons, methane is one of the most potent greenhouse gases [22].

Although it constitutes only 3% of greenhouse gas emissions by mass, methane has the potential to cause global warming that is 84 times more powerful than that of carbon dioxide over a period of 100 years. Therefore, methane is often used as a benchmark in climate change projections. It accounts for approximately 23% of the overall impact of global warming [23,24].

There is a unique opportunity to mitigate methane emissions, as the most cost-effective technologies and practices to reduce emissions from the main human contributors are already widely available and in use around the world. Reducing methane emissions not only helps mitigate climate change but also offers various energy, health, and safety benefits, along with positive local environmental impacts (Fig. 13). Many methane abatement technologies and practices also lower emissions of volatile organic compounds and hazardous air pollutants, improving local air quality.

Projects aimed at reducing methane from landfills and wastewater treatment plants can eliminate unpleasant odors. In agriculture, such practices manage manure to safeguard the local water bodies and environment. Coal mine-gas is a gas that is very safe to capture because it helps in reducing chances of explosions that could result to industrial accidents. Low emitting equipment and enhanced management techniques in oil and gas systems can reduce the emission of methane gases, which has health and safety advantages but adds to the quantity of products released to the market and adds to the revenues. In addition, the recovered methane can be used as a local source of clean energy and as one that fosters economic development. It can replace energy sources that have higher CO₂ emissions and pollutants, such as wood, coal, and oil. Additionally, recovered

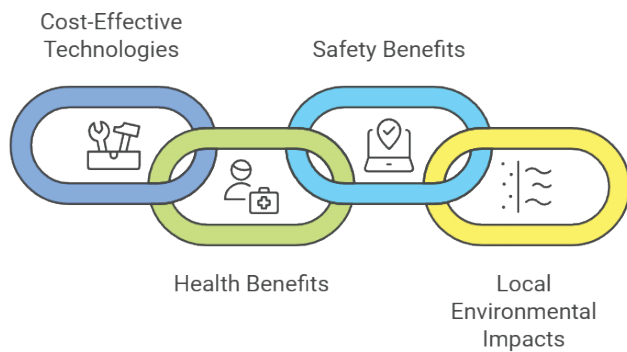


Figure 13. Methane emissions mitigation.

methane can become a sustainable and abundant energy source in developing countries [25].

The major sources of atmospheric methane may include the following:

1. Agricultural Activities
2. Oil and Gas Operations
3. Coal Mining
4. Landfills
5. Wastewater Treatment

The following is an introduction and explanation of each one of them:

Agricultural Activities

Agriculture accounts for 40% to 46% of global methane emissions, and with the increasing demand for food production, these emissions are projected to rise by approximately 40% by 2050. Enteric methane from ruminant livestock contributes to about two-thirds of these emissions, while rice production accounts for 20%, and managed manure adds another 7% (Fig. 14). Several scenarios have been developed to mitigate agricultural methane emissions by 54% compared to potential emissions in 2050, and by 36% compared to current levels.

The mitigation opportunities include [26]:

- Improving feed efficiency for ruminants
- Promoting alternative sources of animal protein
- Implementing effective water management in rice fields
- Establishing a unified mechanism to reduce methane emissions from managed manure
- Raising awareness and addressing food waste globally.

Oil And Gas Operations

In 2020, oil and gas operations worldwide emitted more than 70 million tons of methane, according to the International Energy Agency (IEA). Most of this data was

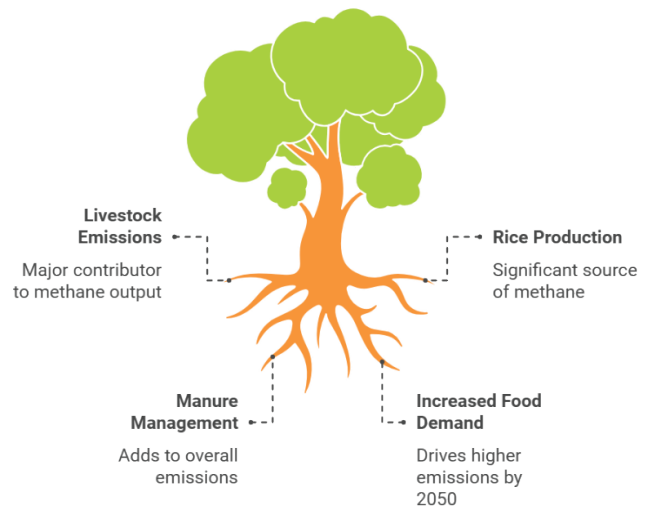


Figure 14. Methane emissions sources from agriculture.

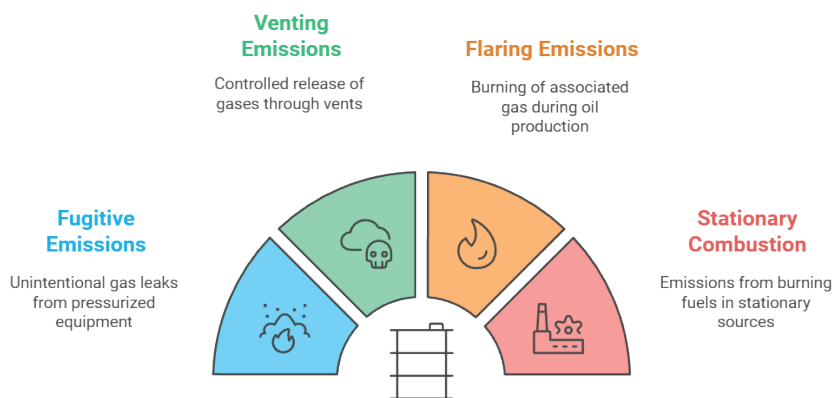


Figure 15. Methane emissions from oil & gas operations.

derived from upstream operations, which include drilling, production, and treatment.

Methane emissions, in oil and gas industry are classified into four categories based on the GHG emission classification and international standards, as follows (Fig. 15) [27]:

- Fugitive: emissions resulting from unintentional loss of the gas phase from equipment containing over-pressurized fluid.
- Venting: emissions related to the intentional control release of gases directly into the atmosphere resulting from the process design, most typically through a vent pipe, seal, or duct.
- Flaring: emissions resulting from burning the “associated” gas that accompanies oil production or simply releasing it to the atmosphere.
- Stationary Combustion: Emissions from stationary combustion include boilers, heaters, furnaces, kilns, ovens, flares, thermal oxidizers, dryers, and any other equipment or machinery that combusts carbon-bearing fuels or waste stream materials.

Coal Mining

Methane is produced during the process of coalification, which is the formation of coal. A small portion of this methane remains trapped in the surrounding rock layers

and coal seams (Fig. 16). This trapped methane is released during the fracturing of the coal seam.

Generally, deeper seams contain a higher concentration of gas compared to those accessed by surface or open-pit mining. As a result, underground coal mining tends to release more methane into the atmosphere [28].

Landfills

Landfills release mostly methane when organic waste is decomposed by bacteria. The landfill gas primarily consists of methane and carbon dioxide (90% to 98%), while the remaining 2% to 10% includes nitrogen, oxygen, ammonia, hydrogen, and other gases. Figure 17 explained the factors contributing to methane emissions from landfills as fish bone diagram.

In landfills, any increase in temperature or moisture can lead to a higher gas output. Although gas production typically peaks within five to seven years, a landfill can continue to generate gases for over 50 years [29].

Wastewater Treatment

In 2010, methane emissions from wastewater were estimated to produce 512 million metric tons of CO₂ equivalent (MMTCO₂E) globally, accounting for nearly 7% of all methane emissions worldwide. Methane is released during the handling and treatment of municipal wastewater

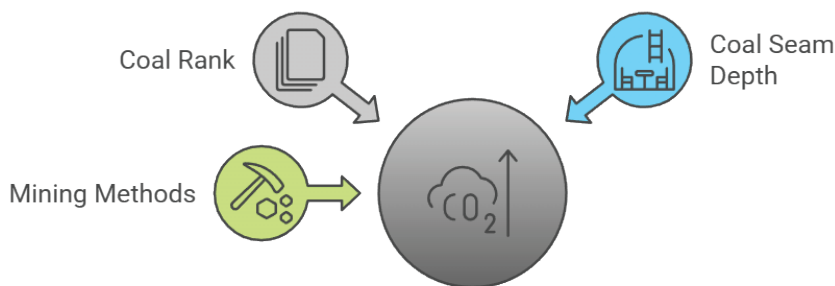


Figure 16. Factors contributing to methane emissions from coal mining.

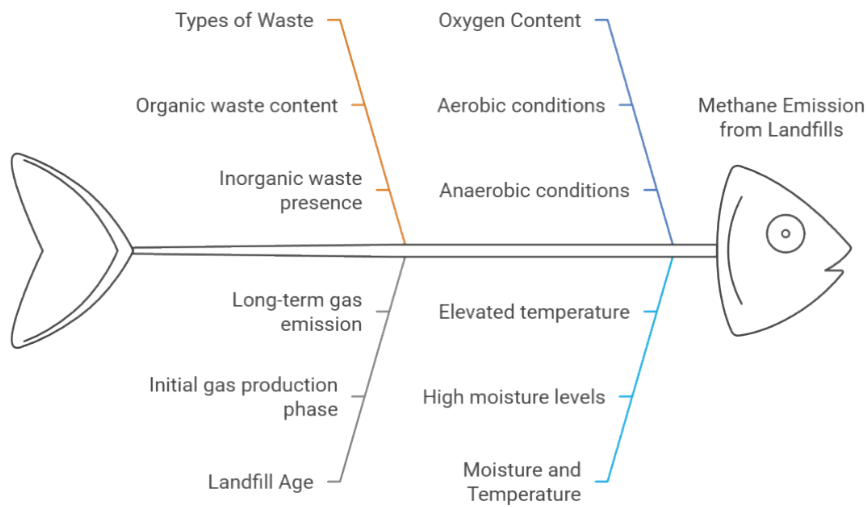


Figure 17. Factors contributing to methane emissions from landfills.

because of the anaerobic decomposition of organic materials. Most developed countries use centralized aerobic wastewater treatment systems to collect and process municipal wastewater. While these systems generate lesser amounts of methane, they also produce significant quantities of biosolids, which can lead to higher rates of methane emissions (Fig. 18) [30].

In conclusion, Table 2 compares the major sources of methane emissions and their description and challenges for each source [26-30]. From these five sources, methane can be used in some industrial applications such as hydrogen for ammonia synthesis, acetylene by exposure to an electric arc, methyl chloride by chlorination, hydrogen sulfide by reaction with sulfur, oxidation products such as methanol, formaldehyde, formic acid, and nitromethan [31].

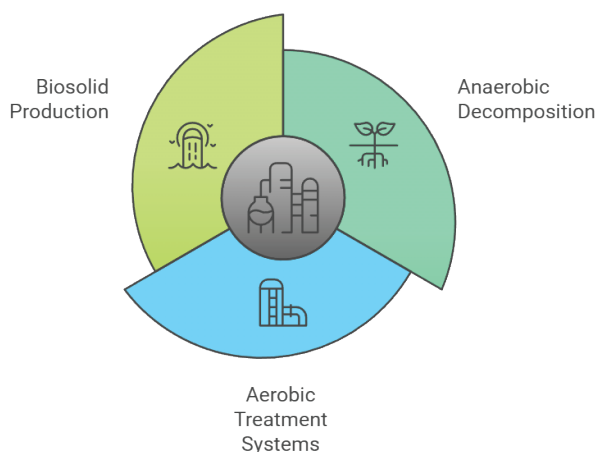


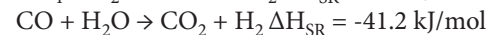
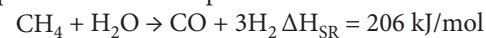
Figure 18. Methane emissions from wastewater treatment.

Extracting Carbon and Hydrogen From Methane

Methane can be used to make hydrogen and carbon by engaging in several chemical reactions. A closed-loop system can be employed by using hydrogen and carbon dioxide that can be used in many industrial applications and processes to increase energy efficiency and decrease emissions [32]. In this section, the various processes along with chemical reactions that use methane to form hydrogen and carbon are introduced as follows:

Steam Methane Reforming (SMR)

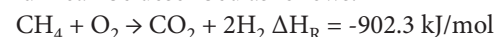
One of the ways of producing syngas is the reaction of methane commonly obtained through natural gas with water steam. Methane is reactive with water steam to form carbon monoxide and hydrogen in this process. Also, more water-steam could be used with carbon monoxide to produce carbon dioxide and additional hydrogen. A chemical equilibrium can be represented as this series of reactions:



The process has about 65-75 efficiency that is one of the highest recorded rates of the existing commercial approaches to production [33].

Autothermal Reforming (ATR)

ATR reacts oxygen with methane producing syngas in one chamber, where methane is partially oxidized. An equilibrium can be described as follows:



The small to mid-scale ATR processes using oxygen instead of air being preferred to use about 40% is an acceptable reforming technology [34,35].

Methane Pyrolysis

The term “pyrolysis” refers to the process of breaking down molecules through the application of heat. In the case

Table 2. Comparison of major sources of methane emissions [created by author]

No	Major Source	Description	Challenges
1	Agricultural Activities	Agriculture is a major source of methane (CH ₄), a potent greenhouse gas that contributes significantly to climate change.	<ul style="list-style-type: none"> ▪ Complex Systems ▪ Require Significant Investments ▪ Technological Limitations ▪ Behavioral Changes ▪ Policy and Regulatory Framework
2	Oil and Gas Operations	The oil and gas industry are a significant contributor to global methane emissions. Methane leaks and venting occur throughout the natural gas supply chain, from production to distribution.	<ul style="list-style-type: none"> ▪ Age and Maintenance of infrastructure. ▪ Remote Operations ▪ Regulatory and Implementing Barriers ▪ Significant Upfront Costs
3	Coal Mining	It is an important origin of methane. Coal seams contain a natural supply of methane which is emitted when disturbances occur to the seams during mining processes.	<ul style="list-style-type: none"> ▪ Technical Challenges ▪ Regulatory Challenges ▪ Safety Concerns ▪ Infrastructure Limitations
4	Landfills	Methane which is a powerful greenhouse gas emits in landfills. An anaerobic (the absence of oxygen) breakdown of the organic material in the landfill emits methane gas.	<ul style="list-style-type: none"> ▪ Waste Composition ▪ Landfill Design and Operation ▪ Regulatory Framework ▪ Public Awareness and Behavior
5	Wastewater Treatment	Methane may be a major source of wastewater treatment plants, especially those that take part in anaerobic digestion. Anaerobic digestion is a natural process that organic matter is dismantled by microorganisms without oxygen, resulting in the formation of biogas, which are mainly made up of the matter of methane and carbon dioxide.	<ul style="list-style-type: none"> ▪ Process Optimization ▪ Energy Efficiency ▪ Methane Capture and Utilization ▪ Public Perception and Regulatory Framework

of methane, heat is used to decompose methane molecules, resulting in the production of hydrogen, often referred to as “turquoise hydrogen.” Additionally, the pyrolysis of methane generates solid carbon as a byproduct, which can be easily stored and repurposed in various industries, such as tire and rubber production. Methane pyrolysis has an energy efficiency of 58%. [36].



Using Hydrogen In Energy Processes

Hydrogen storage is a crucial aspect of the hydrogen value chain that has not been thoroughly addressed until an integrated hydrogen economy is established. The absence of a viable business model for hydrogen as either an internationally or locally traded commodity overlooks the fact that, in many cases, hydrogen needs to be stored immediately after production and before it reaches the end user. Currently, hydrogen is primarily consumed close to where it is produced, mainly for industrial purposes such as oil refining and ammonia fertilizer production. As a result, the significance of storage in the hydrogen value chain has often been underestimated. To enhance hydrogen circulation, it is essential to consider the characteristics and challenges related to storing hydrogen in various quantities for different durations [19].

As shown in Figure 19, hydrogen can be stored in three combined cases (gaseous, liquid and solid), where it can be divided into six main types according to different conditions:

1. Compressed Hydrogen
2. Liquefied Hydrogen
3. Liquid Organic Hydrogen Carriers (LOHCs)
4. Chemical Hydrides
5. Metal Hydrides
6. Porous Materials

Pure Hydrogen Storage

Hydrogen can be stored in a highly compressed form at 700 bar. It can also be kept in a cryogenic liquefied state at -253 °C or in a hybrid form. At 700 bar, hydrogen has a physical limit for volumetric density of 1.3 kg/m³, which provides an acceptable level of energy density at a reasonable cost. Gaseous hydrogen can be stored in closed systems without losses for extended periods. Liquid hydrogen has higher storage densities compared to gaseous hydrogen. At 2 bar, liquid hydrogen achieves a volumetric limit of 2.3 kg/m³, although its boiling point is exceptionally low at -253 °C (Fig. 20). Through greater effort in production and storage, larger energy densities can be reached using liquid hydrogen storage particularly when large amounts of

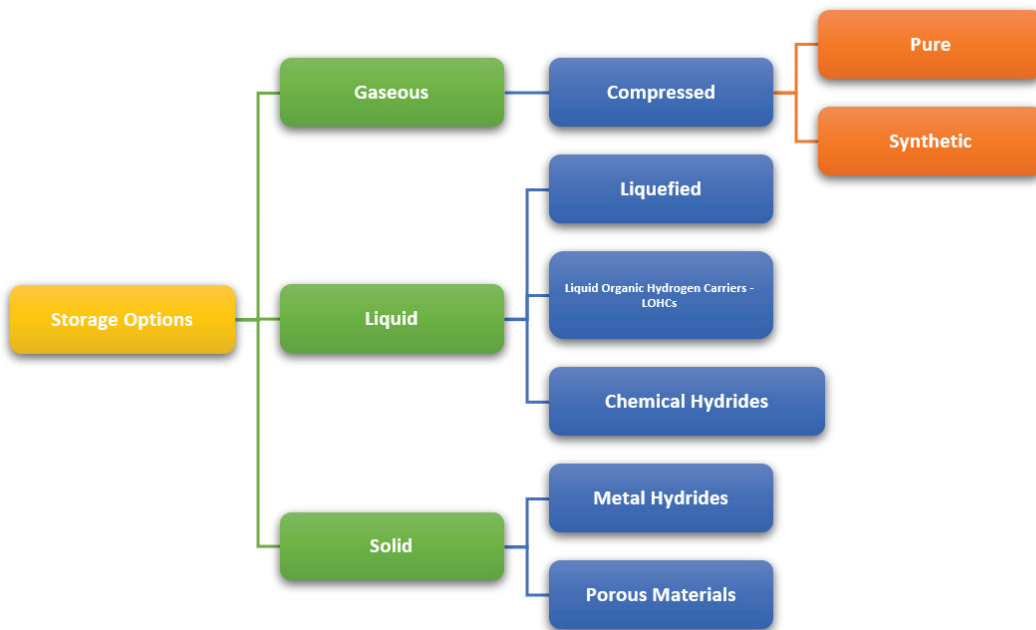


Figure 19. Different hydrogen storage options.

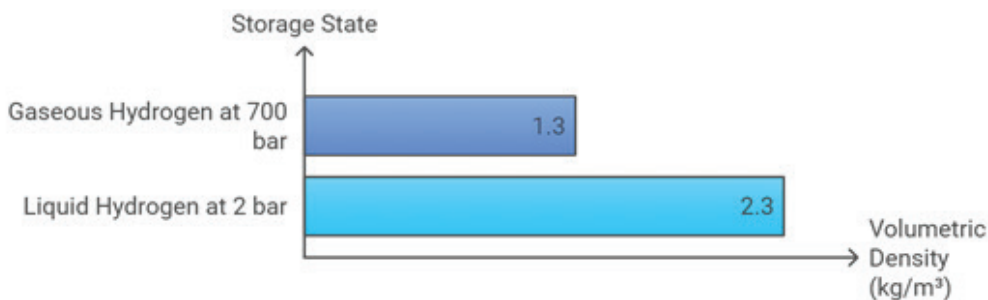


Figure 20. Volumetric density of hydrogen in different storage states.

energy are required, like in centralized production, delivery or space applications such as rocket fuel [37].

Pure hydrogen storage can be utilized centralized; however, it is imperative to adhere to all safety requirements due to its classification as an explosive material.

Synthetic Hydrocarbons

Synthetic hydrocarbons are fuel types produced out of renewable energy sources rather than fossil fuels that are not renewable. They contain equal quantities of chemicals to conventional fuels such as gasoline. These hydrocarbons offer an easy substitute to fossil fuels, such as oil, coal and natural gas as well as all their derivatives. Recent technology demonstrations have demonstrated

that one can use a combination of renewable energy with waste carbon sources- such as biomass or recycled CO₂ to generate synthetic hydrocarbons like methanol, dimethyl ether and synthetic methane (Fig. 21). The fuels can be used as an alternative to fossil fuels in a number of industries such as transportation, chemicals, electricity production, and heating. This transition has the potential to decrease greenhouse gas emissions by a large margin and also reduce the dependence on diminishing stocks of fossil supplies. Finally, by capturing and recycling carbon and sending it back to the origin of synthetic hydrocarbon manufacture, the whole process could theoretically be carbon-neutral, a process that is known as closing the loop [38-40].

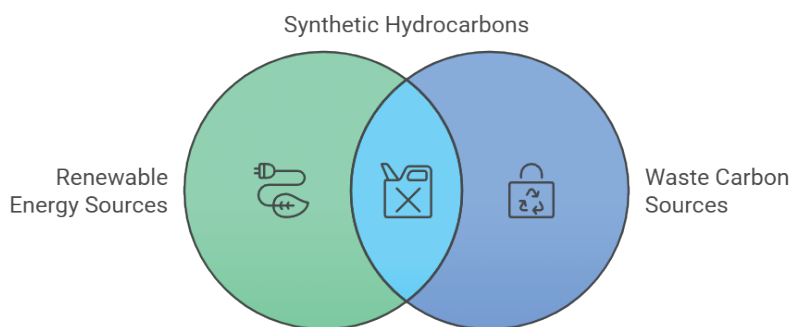


Figure 21. Pathway to carbon-neutral energy.

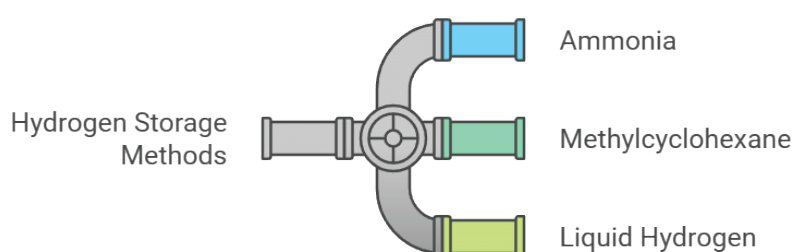


Figure 22. Different chemical hydrides pathway for hydrogen storage.

Chemical Hydrides

Chemical hydride storage methods are one of the many ways to store hydrogen. This category encompasses a wider range of chemicals than synthetic hydrides, yet they generally share similar storage characteristics. The primary advantages of chemical hydride storage include low energy consumption and the absence of a need for infrastructure development. Additionally, their production and dehydration processes tend to require less energy, resulting in lower overall costs. Ammonia, methylcyclohexane, and liquid hydrogen are being researched globally in conjunction with hydrogen storage methods, particularly for the transportation of massive quantities of hydrogen over long distances (Fig. 22). While practical applications of these techniques are promising, they remain in the experimental phase and are awaiting future results [41].

Liquid Organic Hydrogen Carriers (LOHCS)

Liquid organic hydrogen carriers (LOHCs) operate on the principle that organic molecules can chemically bond with hydrogen. Unsaturated hydrocarbon molecules, such as ammonia and methanol, contain high-density double bonds. Storing and transporting hydrogen using LOHCs has a low hazard profile. While a high flashpoint does not eliminate all risks, it, combined with storage and transport at ambient temperature and pressure, significantly reduces the likelihood of leaks, sprays, ignition, and fires. However, the primary concern associated with LOHCs is their aquatic toxicity, see Figure 23 for the pros and cons of using LOHC [42].

Currently, some of the most promising LOHCs that are attracting the most attention from researchers are as follows:

- Toluene/Methyl-Cyclohexane MCH (C_7H_8/C_7H_{14}),
- Naphthalene/Decalin ($C_{10}H_8/C_{10}H_{18}$)
- Benzene/Cyclohexane (C_6H_6/C_6H_{12})

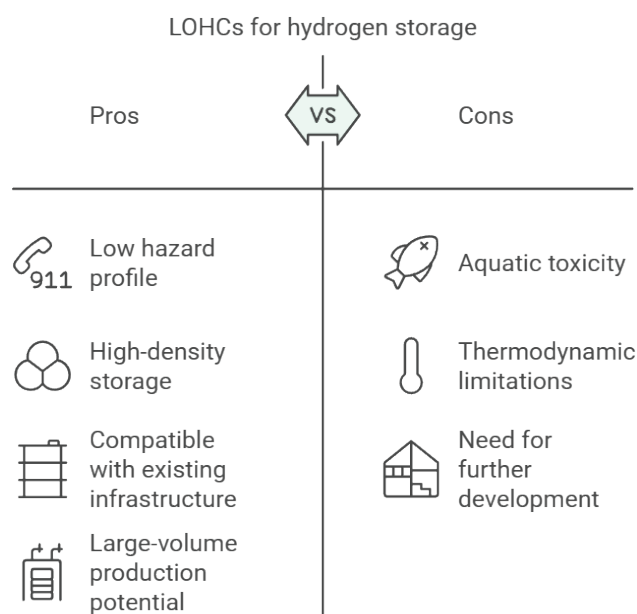


Figure 23. LOHCs pros & cons.

- Dibenzyl/Toluene DBT
- Perhydro-dicenzyl toluene PDBT ($C_{21}H_{20}/C_{21}H_{33}$)

LOHC systems have several attractive characteristics that are like those of crude oil, making them well-suited for integration with existing energy infrastructure. Among these systems, those based on toluene and dibenzyl toluene are particularly suitable for large-scale production. However, further development of LOHC technology is necessary, particularly from a thermodynamic standpoint. Lower dehydrogenation enthalpies would lead to reduced heat requirements and enhance both the molecular stability and recyclability of the candidate molecules over multiple cycles [43,44]

Metal Hydrides

Metal hydrides represent a diverse range of materials that can stabilize hydrogen in a concentrated solid form. In this process, hydrogen bonds with metallic elements and alloys, allowing for some of the highest volumetric densities of hydrogen storage available. In simple terms, hydride is the annoyance of hydrogen. It is a chemical compound in which hydrogen atoms display nucleophilic, basic, or reducing properties.

Some applications of metal hydrides include hydrogen storage and compression, heat pumps and refrigerators, battery electrodes, temperature sensors, and actuators [45].

The boron-nitrogen-hydrogen-containing compounds (BNHC) hold significant promise for enhancing hydrogen storage systems. Among these compounds, ammonium borane (NH_3BH_3 , AB) stands out as one of the most attractive options due to its high hydrogen content (19.6% by weight) and favorable properties such as stability, transportability, and non-toxicity, making it an environmentally friendly hydrogen carrier.

Hydrogen can be efficiently generated from an aqueous solution of AB at a pH value higher than 7 in the presence

of catalytic materials through a hydrolysis process under ambient conditions [46].

Overall, the main advantages of metal hydrides are their high volumetric density, low operational pressure, and endothermic reaction during desorption. However, there are also drawbacks, such as the required operating temperature, hydrogen sorption kinetics, cost, and potential pyrophoricity (Fig. 24).

Currently, this option is still under research and development before metal hydrides can become a viable solution for large-scale hydrogen storage [45].

These metal hydrides include the following:

- Ionic or Saline Hydrides: NaH - CaH_2
- Covalent Hydrides: SiH_4 - $Al(BH_4)_3$
- Metallic Hydrides: TiH_2 - $LaNi_5H_6$ - $LiAlH_4$ - $NaAlH_4$

Porous Materials

Porous materials are found throughout the environment and are integral to many aspects of daily life. They are utilized in various applications, including energy management, vibration dampening, thermal insulation, sound absorption, and filtration [47].

The amount of hydrogen that can be adsorbed by porous substances at normal temperatures and elevated pressures is often quite low, typically falling below 0.5 wt.% (wt% means weight percent). The effect of temperature on hydrogen adsorption in these materials presents challenges for their use in hydrogen storage, particularly when large storage capacities are required [48].

There are two primary types of porous materials capable of storing significant amounts of hydrogen, (Fig. 25 showing the capacity vs. readiness) [49]:

- Carbon-based Hydrogen such as activated carbon, carbon nanotubes, and graphene, are promising candidates for hydrogen storage due to their high surface area, tunable pore structure, and chemical stability.



Figure 24. Weighing the pros and cons of metal hydrides.

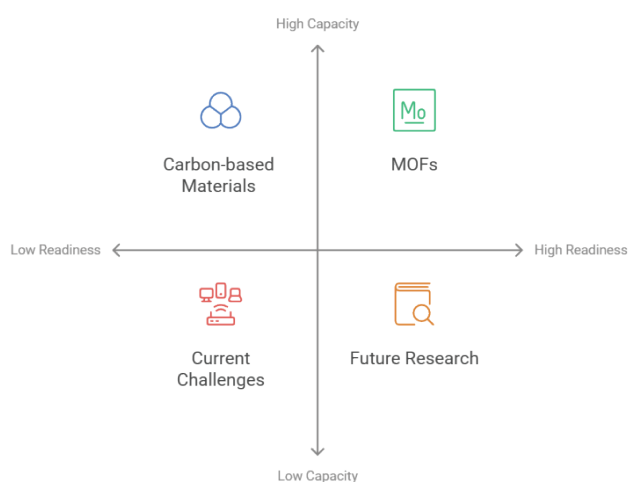


Figure 25. Porous materials for hydrogen storage.

- Metal Organic Frameworks (MOFs) are a class of crystalline, porous materials composed of metal ions or clusters connected by organic linkers. Their highly porous structure, tunable pore size, and large surface area make them promising candidates for hydrogen storage.

Despite numerous efforts to bring these solutions to the market, no one has yet achieved the level of technological readiness necessary for full commercialization, due to the following:

- Require complex synthesis processes.
- It can degrade under harsh conditions, such as elevated temperature, humidity, or exposure to specific chemicals.
- High cost and energy-intensive processes

The following table 3 introduces a comparison of the hydrogen storage options while showing description, advantages, and challenges [19].

Table 3. Comparison of hydrogen storage options

No.	Hydrogen Storage Option	Description	Advantages	Challenges
1	Compressed Hydrogen	It is one of the most common methods for storing hydrogen gas. It involves compressing hydrogen gas to high pressures, typically around 700 bar, and storing it in high-pressure tanks.	<ul style="list-style-type: none"> ▪ Mature technology ▪ High energy density ▪ Flexibility 	<ul style="list-style-type: none"> ▪ Energy intensive ▪ Safety concerns ▪ Storage tanks are too large and heavy ▪ Efficiency losses
2	Liquefied Hydrogen	Making Hydrogen gas cool to very low temperatures (-253°C) converting it to liquid form. This greatly makes it smaller in volume and therefore easier to store and carry around.	<ul style="list-style-type: none"> ▪ High energy density ▪ Efficient storage and transport 	<ul style="list-style-type: none"> ▪ Needs Special Cryogenic Storage Tanks and Packing ▪ Energy intensive ▪ Boil-off losses. ▪ Safety concerns
3	Liquid Organic Hydrogen Carriers (LOHCs)	Are the organic compounds that can store/release hydrogen reversibly exist. These substances might exist as liquid at ambient temperature and pressure and hence easier to process and ship compared to gaseous or liquid hydrogen. Safe and convenient to work with.	<ul style="list-style-type: none"> ▪ Safe and Easy to Handle ▪ High Energy Density ▪ Improving with Existing Fuel Infrastructure 	<ul style="list-style-type: none"> ▪ Lower Energy Density by Volume ▪ Slow Hydrogen Release ▪ Material Cost
4	Chemical Hydrides	Can work with solid materials able to take up and give off hydrogen gas by way of chemical reactions. The materials provide a possible solution to store large quantities of hydrogen in a small size.	<ul style="list-style-type: none"> ▪ High Hydrogen Storage Capacity ▪ Safe and stable 	<ul style="list-style-type: none"> ▪ Slow hydrogen release ▪ Energy-intensive ▪ Not as Well Suited to Transportation
5	Metal Hydrides	Are the solid-state materials exist that are capable of adsorbing and desorbing hydrogen gas. This property renders them a possible solution in storage of large quantities of hydrogen in a condensed form.	<ul style="list-style-type: none"> ▪ High hydrogen storage capacity ▪ Safe and stable ▪ Moderate operating conditions 	<ul style="list-style-type: none"> ▪ Low Hydrogen Absorption/Desorption rates ▪ Sensitivity to impurities ▪ Limited cycle life
6	Porous Materials	They have high surface areas and tunable pore structures which makes them ideal in adsorbing and storing hydrogen gas.	<ul style="list-style-type: none"> ▪ High surface area ▪ Tunable pore structure ▪ Environmental friendliness 	<ul style="list-style-type: none"> ▪ Low storage capacity ▪ Sensitivity to environmental factors ▪ Expensive cost

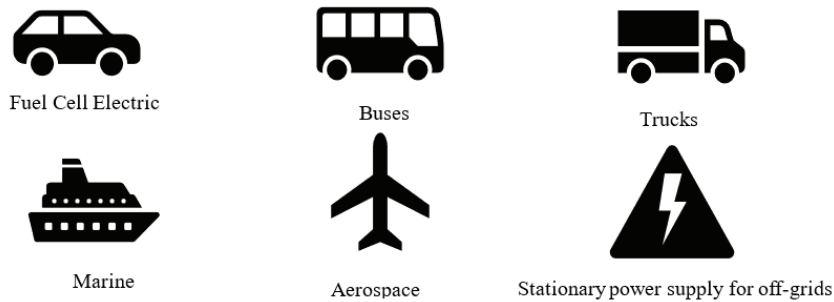


Figure 26. Hydrogen fuel cell applications.

Using Hydrogen Fuel Cells for Transportation and Electricity Generation

Figure 26 shows how the hydrogen is directly used in the transportation sector via fuel cells (FCs). A fuel cell is an electrochemical apparatus that reacts hydrogen and oxygen to create electricity and water and heat is the byproduct. Simply, a fuel cell is composed of two electrodes; the anode and the cathode with an electrolyte in the middle. At the anode, hydrogen is reacted with a catalyst, which produces a positively charged ion, and a negatively charged electron. The electric current then flows through an external circuit as the positively charged ion (proton) flows through the electrolyte and the electron flows through the electron circuit. At the cathode the oxygen reacts with the ions and electrons to produce water and liberate productive heat [50].

Aviation

Decarbonization is one of the largest problems of the aviation industry. The current level of CO₂ emitted by the aviation is more than 900 million tons/year. When the industry keeps growing with an average of 3 to 4 percent / year and the industry becomes more efficient with an average of 2 percent every year, then the CO₂ emissions would be much higher in 2050. In the same timeframe, the Air Transport Action Group (ATAG) has also established an aim to cut down on CO₂ emissions by half of the current situation in 2005 and the European Union has also made a target to be a carbon neutral nation by its Green Deal. Besides the production of CO₂ emissions, aircrafts also produce NO_x emissions, soot and water vapor that contribute to the formation of contrails and the formation of cirrus clouds. As a result, the net effect of the aviation to global warming is much higher as compared to the isolated CO₂ emissions. Hydrogen (H₂) propulsion can fundamentally reduce such climate effects. It can break down CO₂ during flights and can be produced in a carbon-free manner. Recent estimates suggest that H₂ combustion alone could cut climate impacts during flight by 50-75%, and by 75-90% when using fuel-cell propulsion, compared to a reduction of about 30-60% with synthetic fuels [51,52].

To scale H₂-powered aviation, several actions need to be taken [53]:

- Lighter tanks (aiming for 12 kWh/kg/ gravimetric index 35%) to improve overall efficiency and fuel cell systems (aiming for 2 kW/kg including cooling).
- Liquid Hydrogen (LH₂) distribution inside the aircraft and Turbines can burn hydrogen with low NO_x emissions.
- The development of high efficiency refueling technologies that can provide the same flow rates as kerosene.

Maritime Applications

The marine sector is responsible for transporting over 80% of global goods through international shipping routes, consuming more than 330 million tons of fuel each year. An important part of transport is also played by ferries; says the United States Bureau of Transportation Statistics of 2015, almost 119 million passengers and 25 million vehicles were transported by ferries in the United States. U.S ferries used 48.6 million gallons of diesel fuel in 2018 and the subsequent 494,000 metric tons of CO₂ emissions each year. The maritime sector is considering fuels like liquefied natural gas (LNG), biofuels, and electric propulsion to cut emissions by using batteries and/or fuel cells using hydrogen (Fig. 27). Renewable hydrogen power can be used to greatly reduce or even eliminate the emissions in marine operations.

Nonetheless, due to the prevailing low cost of low-sulfur marine gasoil (LSMGO), competing of hydrogen fuel in container ship business is not easy. LSMGO is more densely volumetric and that is more preferable in longer voyages. As much space to hold the quantity of hydrogen necessary to supply the energy requirements during such voyages is larger than what a similar lengthy distance by diesel-powered ships would have consumed in terms of cargo carrying and revenue generation. Fuel costs account for approximately 87% of the total cost of ownership (TCO) in the maritime sector. The lower efficiency of fuel cells compared to diesel engines, in terms of energy output during regular operation, does not offer sufficient energy savings to justify the higher cost of hydrogen fuel, which is currently around \$2 per kilogram compared to LSMGO [54].

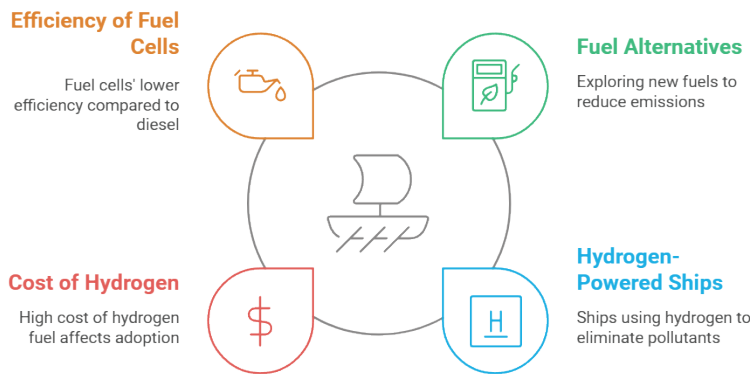


Figure 27. Factors influencing maritime emissions reduction.

Ground Vehicles

There are two primary alternatives to conventional internal combustion engine (ICE) vehicles for reducing greenhouse gas (GHG) emissions:

- Hydrogen Fuel Cell Vehicles (HFCVs).
- Battery Electric Vehicles (BEVs).

Both types of vehicles produce zero tailpipe emissions and have the potential to significantly lower emissions in the transportation sector by utilizing electricity or low-emission hydrogen, (Fig. 28). The current increase in the commercialization of hydrogen-fueled vehicles (HFCVs) is a result of substantial technological advancements. HFCVs have accumulated over 20 million kilometers in real-world conditions using Polymer Electrolyte Membrane Fuel Cells (PEMFC). Since 2002, the costs of fuel cells have decreased by 80 percent, and the durability of HFCVs has improved fourfold, now exceeding 120,000 miles. As of 2018, there were 11,200 HFCV cars on the road worldwide [55,56].

Electricity Generation

Since most of the energy is generated by burning fossil fuels, power generation accounts about for 25% of all carbon dioxide emissions. Hydrogen will play a crucial role in the future energy mix and can help reduce the carbon footprint of power generation.

Depending on the fuel cell technology, the practical electrical efficiency of fuel cells can range from 40% to 65% at the beginning of their lifecycle. When combined with Combined Heat and Power (CHP) systems, the overall efficiency can exceed 90%, making it an ideal option for hydrogen applications. In the short to medium term, clean hydrogen is likely to remain expensive, which highlights the importance of power generation efficiency in the project's economic model. Since hydrogen prices can differ based on the production process, transportation methods, geographical location, and other site-specific conditions, electrical efficiency plays a significant role in the economics of projects involving hydrogen. A new generation of solid oxide fuel cells (SOFCs) presents several inherent advantages over traditional fuel cell technologies. These advantages include high efficiency, stability, reliability, and fuel flexibility. SOFCs can utilize either natural gas (methane) or hydrogen as fuel for the reaction [57,58] Figure 29 presents the role of hydrogen in energy generation.

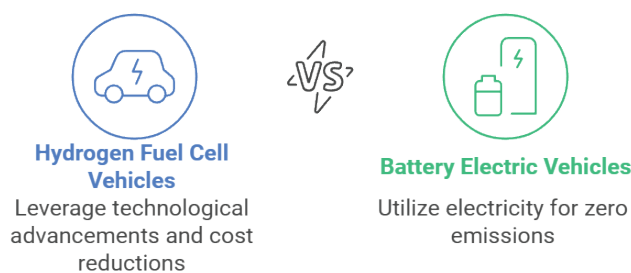


Figure 28. New alternatives to lower-emission vehicles.

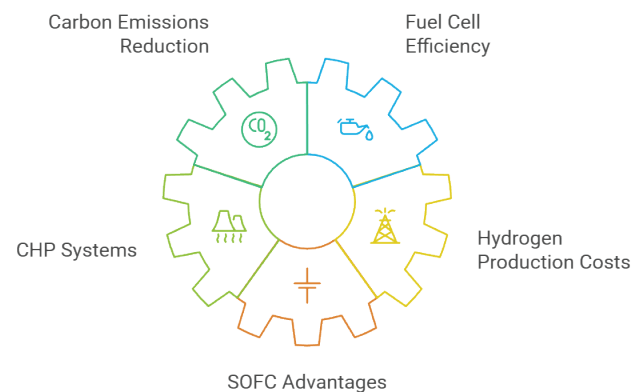


Figure 29. Hydrogen's role in energy efficiency.

DOMESTIC ENERGY

Figure 30 illustrates the domestic use of fuel cells. Along with generating electricity, the heat produced can also be utilized. This process is known as combining heat and power (CHP) transformation. When these systems are applied in the domestic heating sector, they are commonly referred to as micro/mini-CHP plants due to their smaller output capacities [50].

The heat generated by the combination of heat and power is used to partially meet a building's heating needs. Fuel cell heating systems produce low thermal output mainly because they operate primarily on electricity. To address the remaining heating requirements of the building, an additional heating system, such as a condensing boiler, is utilized. Fuel cells are particularly well-suited for structures that require minimal space heating, like low-energy or nearly zero-energy buildings. In contrast, buildings with higher space heating demands use hybrid heating systems that combine a fuel cell with a boiler to satisfy peak heating needs [50,59].

Using Carbon Dioxide In Energy Efficiency & Industrial Processes

Climate change mitigation is a key factor driving interest from governments and stakeholders in leveraging new opportunities to utilize CO₂ for developing products and services. This also aims to promote technological leadership and support the circular economy [60]. Figure 31 introduced some pathways to a circular carbon economy related to carbon dioxide. The use of CO₂ has the potential to significantly contribute to achieving net-zero greenhouse gas emissions in the future. CO₂, a greenhouse gas, can be captured from the Earth's atmosphere, water, or waste gas streams and chemically transformed into commercially viable carbon-based products. The U. S. Congress, as part of the Energy Act of 2020, teamed up with various national academies to examine the prospects and obstacles of moving forward with improvements in CO₂ capture technology, infrastructure, and CO₂-based product markets. The goal is to integrate carbon waste streams in a circular carbon economy. The application of carbon is a core element to

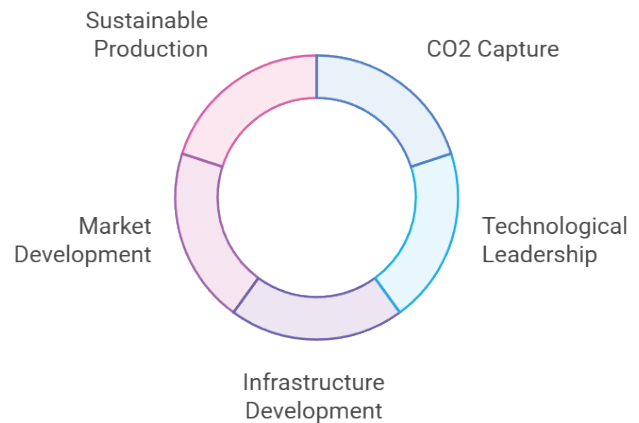


Figure 31. Pathways to a circular carbon economy.

several products, namely plastics and commodity chemicals. Nevertheless, the existing production technologies are based on the extensive use of fossil fuels and carbon input based on heat, power, and transport powered by fossil fuels. A net-zero-carbon economy will require that the carbon-based products be produced in a sustained manner that no net CO₂ emissions are emitted into the atmosphere.

Today, industrial-scale CO₂-based products include urea, organic carbonates, methanol, salicylic acid, and CO₂-treated concrete. However, these products generally do not achieve net-zero emissions at any point in their lifecycle. Pilot-scale initiatives are being developed to create additional commercial products, but they face challenges such as a lack of low-carbon product incentives, the inherently higher costs and energy requirements of using CO₂ for hydrocarbon products compared to readily available fossil carbon, and the need for clean hydrogen, electricity, and heat as inputs. CO₂ is subject to a chemical change that creates long- and short-lived products. Indicatively, the concrete and aggregates may last over 100 years since they are capable of storing carbon. These materials are sustainable to be manufactured by fossil, atmospheric or bio-based CO₂ as in Figure 32. In contrast, short-lived products, such as chemical intermediates and many plastics, have shorter

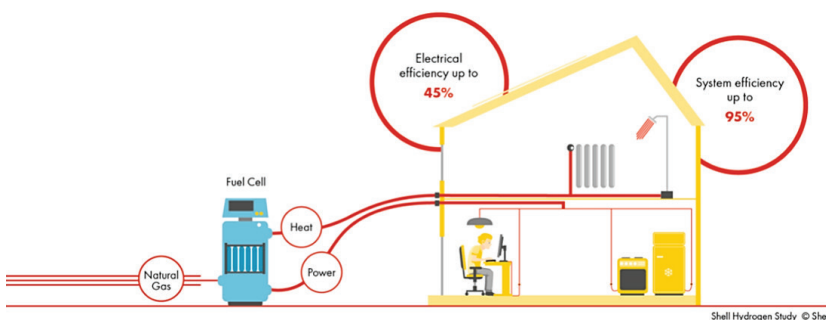


Figure 30. Hydrogen fuel cells in domestic energy usage [created by author].

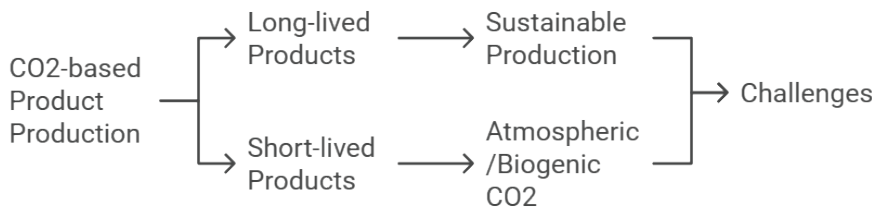


Figure 32. CO₂-based products pathway.

lifespans and only temporarily remove CO₂ from the atmosphere because they eventually degrade back into CO₂ at the end of their life cycle. Therefore, the production of short-lived products requires CO₂ derived from either the atmosphere or biogenic sources in a way that allows the embodied carbon to contribute to the circular flow of CO₂ in the atmosphere [61].

The key categories of products and services derived from CO₂ that are anticipated to see new developments in the short term include the following:

- Fuels
- Chemicals
- Mineral building materials
- Building materials from waste
- Enhancing the yields of biological processes

Each of these categories has the potential to be scaled up to a market size of at least 10 million tons of CO₂ per year, which is comparable to the current CO₂ demand in the food and beverage industry. At present, the technologies for utilizing CO₂ in products and services are still in the development stage, as illustrated in Figure 33 [60].

When an application is scalable, utilizes low-carbon energy, and replaces a product with higher life cycle emissions, the use of CO₂ can contribute to achieving climate goals. In the short term, the market for CO₂ utilization will likely remain small, particularly for early opportunities related to building materials. Additionally, public purchases of low-carbon products can help develop technological

standards and create an initial market for these goods. Furthermore, CO₂ sourced from biomass, or the air can play a significant role in ensuring a net-zero economy in the long run, as it can be used as a carbon source for jet fuel and chemicals. [60]. Carbon dioxide (CO₂) can be utilized in several ways. It can be used directly, meaning it retains its chemical state, or indirectly, where it participates in multiple chemical and biological processes. These processes include the production of fuels, chemicals, and building materials.

The interest in CO₂ stems from its potential to help achieve climate objectives. This interest is combined with technological innovation, energy security, and expectation of low-cost, abundant renewable energy sources, which may reduce CO₂ conversion technologies to be more economical. Moreover, the application of CO₂ can be a low-volume source or a low-volume option [62].

The Emerging Market Opportunities for CO₂

Recently, there has been an increased government and industry interest in using CO₂ in other applications mainly due to the need to reduce climate change. The 2015 Paris Agreement established a framework governing the process of intensifying climate programs with the objective of ensuring that the increase in the global average temperatures is below 2°C beyond preindustrial levels. Power plants are responsible for 80% of global CO₂ emissions from large stationary sources, while the remaining 20% originates

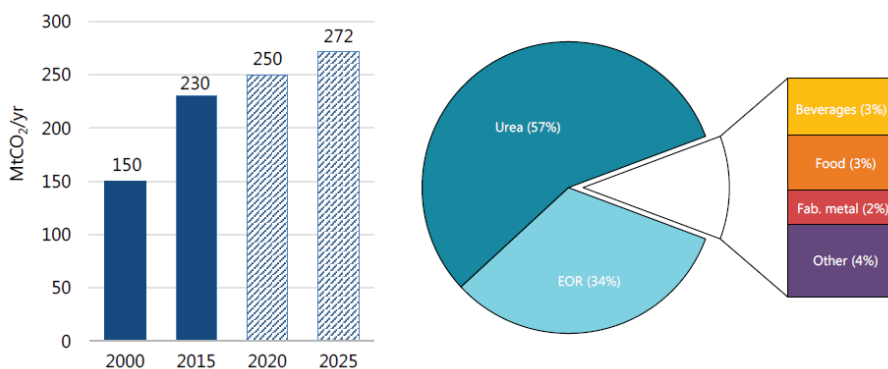


Figure 33. Growth in the global demand for CO₂ over time [created by author].

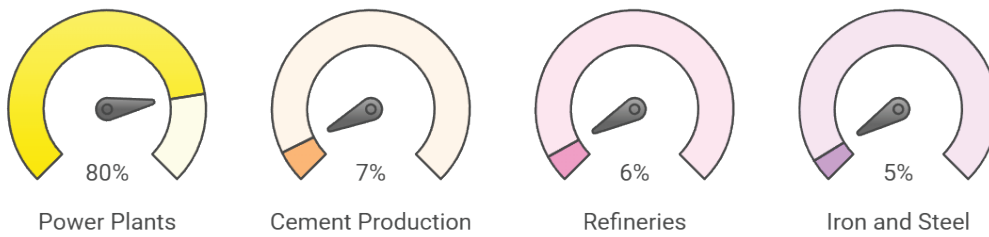


Figure 34. Global CO₂ emissions from different industrial applications.

from industrial sources. The major contributors in this category include cement production plants (7% of total emissions), refineries (6%), and the iron and steel industry (5%), as shown in Figure 34. While modern technologies contribute a smaller overall percentage of emissions, the concentration of CO₂ in flue gas from these industrial sources can be higher than that from power plants. As a result, CO₂ capture processes in industrial settings may be more efficient and can lead to competitive costs for the CO₂ that is avoided compared to power plants. It is also essential to recognize that industrial sources can represent a sizable portion of total emissions, especially in countries where low-carbon energy sources such as nuclear power as in France, and renewable energy (for example, in Scandinavian countries) play a key role in reducing overall emissions. The potential for CO₂ utilization may help in lowering overall emissions and is one of many strategies for mitigating CO₂. Even in a carbon-free economy, carbon will still be necessary for various applications [63,64].

Some examples of emerging applications of CO₂ in industry include the following:

The Cement Industry

CO₂ can be utilized as an input in the concrete production process. In principle, concrete produced with CO₂ can be used for the same applications as conventional concrete, provided that its material properties are similar to or better than those of traditional concrete (Fig. 35). CO₂ curing concrete technology is an innovative method that enhances the performance of cured concrete while being cost-effective and environmentally friendly. This green, low-carbon technology enables the carbonate components in fresh concrete and the calcium silicate in cement clinker to react with CO₂, resulting in the formation of calcium carbonate and silica gel. The raw materials used in CO₂ curing concrete include aggregates, a specific water-to-binder ratio, CO₂ concentration, pressure, and pre-treatment processes. When concrete undergoes CO₂ curing, its micromorphology changes significantly. The surfaces of cement particles and the slurry are coated with calcium carbonate crystals and silica gel. This combination of silica gel and calcium carbonate interlocks, reducing the overall porosity of the concrete and increasing the density of its microstructure.



Figure 35. CO₂ curing concrete process.

Subsequent CO₂ curing leads to a reduction in the inner porosity of the concrete, resulting in a more compact structure that boasts increased hardness, density, and improved resistance to freeze-thaw cycles, weathering, and sulfate exposure. The transition from conventional concrete to CO₂-treated concrete is projected to create a demand for approximately 1,000 MtCO₂ worldwide today, increasing to 1,200 MtCO₂ by 2030. The annual utilization of 10 MtCO₂ corresponds to about 300 million tons of CO₂-cured concrete [65,66]

Chemical Industry

The utilization of CO₂ in chemical and biotechnological processes involves using it as a reactant in various chemical and biochemical reactions. This concept of employing CO₂ in chemical reactions is not new; several established reactions are already based on this idea. Products derived from CO₂ include basic chemicals, polymers, specialty chemicals, and synthetic chemicals. However, it can be challenging to categorize CO₂-based products strictly as chemicals or fuels. For example, some substances, like methanol, fit into both categories, as illustrated in Figure 36. Currently, approximately 110 million tons of carbon dioxide are used as a raw material in the chemical industry. The primary applications of CO₂ as a raw material include

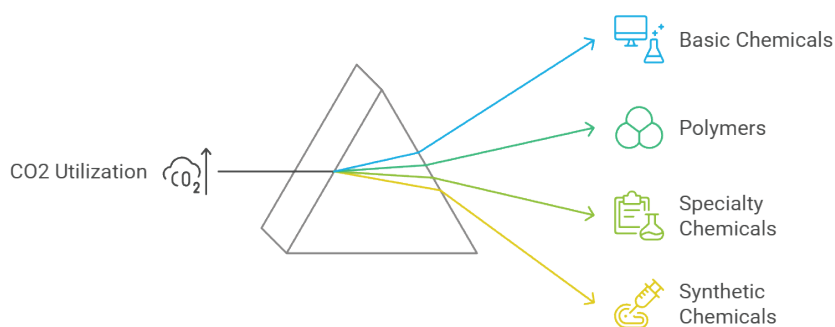


Figure 36. Diverse pathways of CO₂ utilization.

the production of synthesizers and products such as urea, methanol, polymers, and formic acid [67].

However, the following are some chemical industries using CO₂ in their processes:

Methanol Synthesis

The industrial process that utilizes CO₂ as a reactant involves adding small amounts of it to hydrogen-rich synthesis gas to produce methanol. Currently, the world produces approximately 80 million metric tons (Mt) of methanol annually, using about 2 million tons (Mt) of CO₂ in the process. While the direct synthesis of CO₂ and hydrogen from methanol has not yet been implemented on a large industrial scale, it is already in use at a few small commercial plants, Figure 37, show the taken steps in synthesis methanol production [67].

Synthesis of Urea

The urea synthesis reaction involves the combination of carbon dioxide (CO₂) and ammonia to produce urea. Urea serves as a nitrogen fertilizer and as a raw material in the chemical industry to produce various chemical products, including urea resins. These resins can be used

for adhesives, impregnation, and insulation purposes. Approximately 150 million metric tons of urea are produced annually, using about 110 million tons of CO₂ in the synthesis process. Typically, the synthesis units for ammonia and urea are integrated, meaning that the CO₂ used in the urea synthesis is sourced directly from the ammonia production process [68].

Polymers

Polymers are chemical substances made up of many repeating units of the same groups of atoms, organized into linear or branched chains. The term “plastic” typically refers to synthetic polymers. The production of plastics involves linking together chemicals known as monomers, which form the polymer.

Carbon dioxide (CO₂) can be used as one of the monomers and can be incorporated directly into the polymer chain. Alternatively, the polymer can consist of monomers that have been synthesized beforehand using CO₂. The chemical industry foresees that plastic products that are based on CO₂ will result in innovative products that possess new or enhanced material properties. Moreover, the use of CO₂ in plastic production could be more sustainable,

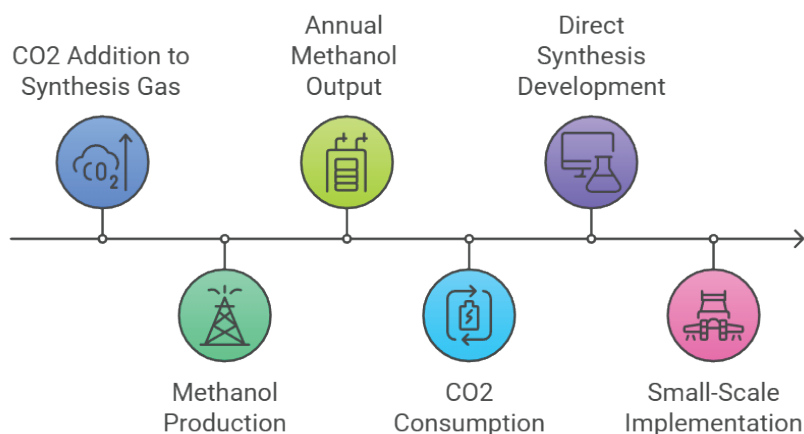


Figure 37. CO₂ Utilization in Methanol Production.

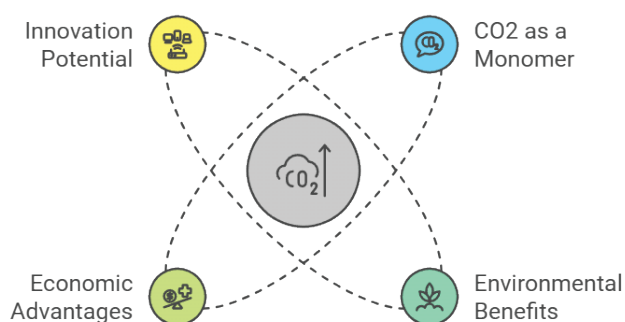


Figure 38. The role of CO₂ in plastic production.

leading to a decrease in the processing of CO₂ emissions and the dependence on fossil fuel.

One of the key advantages of CO₂-derived compounds is that they provide a carbon-containing molecule that is often less expensive and has a smaller environmental impact than its fossil fuel-based counterparts, as introduced in Figure 38. Some chemical feedstocks cannot be decarbonized because carbon is essential for their structure and properties. Along with biomass and waste, carbon dioxide (CO₂) is one of the few carbon-building blocks that can serve as a raw material for carbon-containing chemicals [69].

Synthetic Fuel

Synthetic fuel is not a new concept. In general terms, it refers to any fuel that is not derived from fossil fuels. Synthetic fuels can be used to prevent the green house gas emissions which would arise due to the combustion of fossil fuels like petrol and kerosene yet they offer the same energy density and meet the international standards of fuel. Synthetic fuels can be used as an alternative to fossil fuels since they are a carbon-neutral source of energy and can be used to curb the frequency of fossil consumption among us. Synthetic fuels do not require limited resources like the use of carbon and hydrogen through the input of organic waste feed into biofuels and thus can be reproduced in large volumes.

The production of synthetic fuels can utilize carbon dioxide from various sources, including point sources like industrial emissions, or through carbon removal techniques such as direct air capture. Figure 39 presents a comparing between synthetic & biofuels according to capacity and resources. With supportive government policies emerging in many countries to unlock the potential of synthetic fuel production, now is an ideal time to establish future markets and regulatory frameworks that can stimulate demand [70].

FOOD & BEVERAGE INDUSTRY

Carbon dioxide is commonly used in the beverage industry for carbonation. It also plays a crucial role in controlling atmosphere storage and modified atmospheric

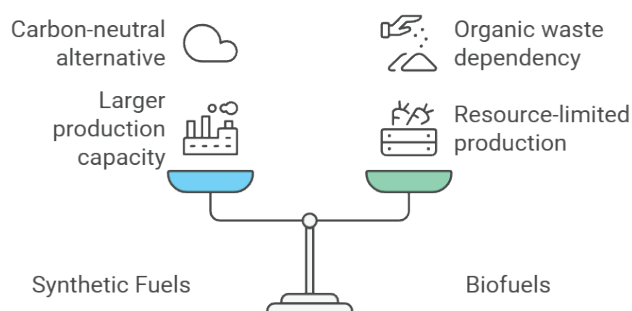


Figure 39. Comparing synthetic & biofuels: capacity & resources.

packaging, which helps reduce spoilage, eliminate insect pests, and extend the shelf life of packaged foods such as grains, fruits, vegetables, meats, and processed foods. Additionally, liquid, and supercritical CO₂ are utilized for extracting flavors, oils, and other chemical compounds, such as in the decaffeination of coffee and tea. CO₂ also finds applications in food processing within the baking, dairy, and other industries. Furthermore, dry ice and liquid CO₂ are employed in freezing and refrigeration processes, as shown in Figure 40 [71].

Inactivation of Enzymes

Lipolytic microorganisms, such as psychrotrophic bacteria, are commonly found in fatty foods. These bacteria produce enzyme lipases during storage, which leads to rancidity and negatively impacts food quality. Research has shown that carbon dioxide gas can effectively inactivate the lipase enzyme; approximately 84% of the enzyme's initial activity is lost within just five minutes when exposed to carbon dioxide at an initial pH of 7.15 and a temperature of 50°C. Furthermore, carbon dioxide treatment, applied under atmospheric pressure, presents promising

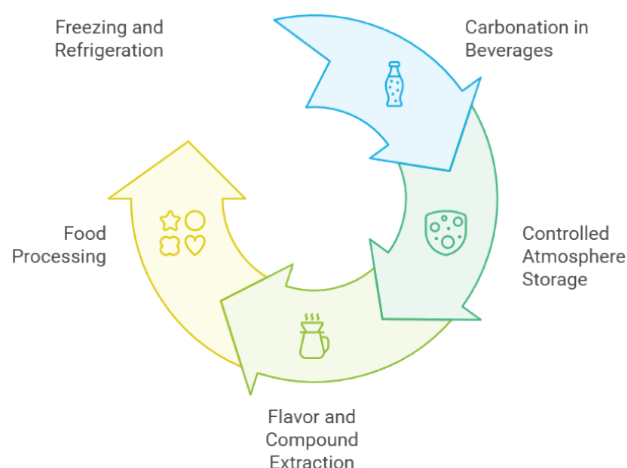


Figure 40. CO₂ utilization cycle in food industries.

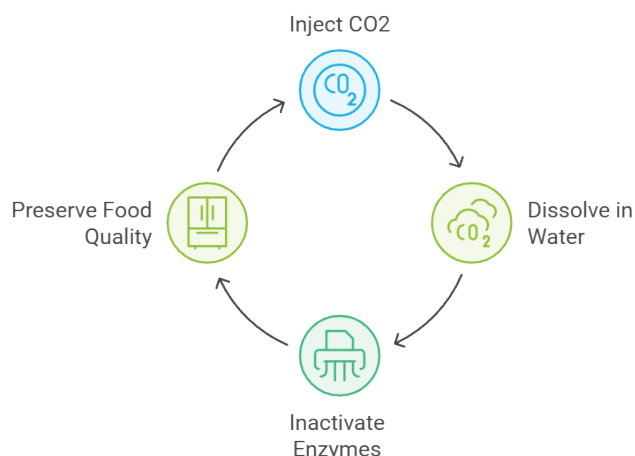


Figure 41. Carbon dioxide treatment cycle.

non-thermal technology for preserving liquid foods. This method can also be effective in inactivating enzymes that require high pressure. By injecting carbon dioxide through submerged water, the oxygen content is reduced, which inhibits enzymatic browning in pre-peeled potatoes without adversely affecting their hardening, thanks to the increased acidity of the water.

Figure 41 shows the carbon dioxide treatment cycle in inactivation of enzymes. In modified atmosphere packaging or controlled atmosphere storage, carbon dioxide inactivates enzymes by dissolving in the water present in the product [72].

Protein Precipitation

A continuous process has been developed for the precipitation of casein, the primary protein extracted from milk and the main ingredient in cheese, using carbon dioxide at a pressure of less than 14 MPa in a tubular reactor.

The optimal casein product is obtained at temperatures of 38°C and a pressure of 5.52 MPa. Instead of lactic or mineral acids, casein precipitation with CO₂ is advantageous since the area remaining after precipitation is relatively high, i.e. 6.0, thus there is less pretreatment in comparison to other conventional methods. Also, it was possible to precipitate soy protein by the use of high-pressure carbon dioxide with sizes attaining approximately 68.3% (by weight) of precipitation owing to the use of 3.0 MPa pressure, pH 5.6 and constant temperature of 22°C. In contrast to traditional mineral oil-based precipitation methods, high-pressure CO₂ precipitation is a cleaner process. It produces highly purified food protein without the need for further purification before use in food and non-food applications, as introduced in Figure 42 [72].

Monitoring Food Quality

The use of carbon dioxide extends beyond preserving and processing food products; it also serves as an indicator of changes in the quality of food materials during processing and storage. This is done by observing changes in the concentration of carbon dioxide in the grain storage bins where growth and infestation of insects and microorganisms like fungi are observed. After determining the impact of humidity, temperature and the mechanical damages on the carbon dioxide that is generated by grains such as corn and wheat during storage, we can measure the dry matter loss which is a sign that the grain is deteriorating. Consequently, linking carbon dioxide levels with grain quality will help determine the optimal conditions—such as humidity and temperature—for storing grains effectively and maintaining their quality, as shown in Figure 43 [72].

Carbonated Beverages

The most common and oldest use of carbon dioxide (CO₂) is in the production of carbonated soft drinks and soda water. CO₂ enhances the distinctive sharp taste or

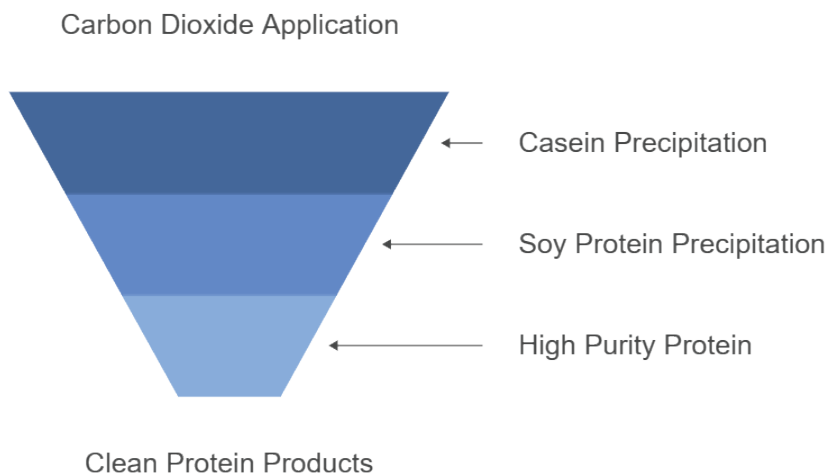


Figure 42. Efficient protein precipitation process.

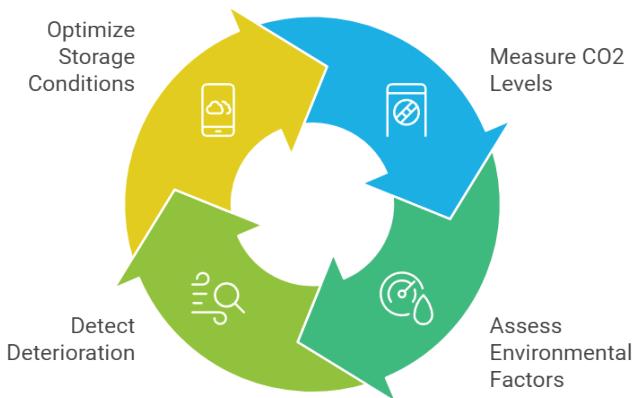


Figure 43. Carbon dioxide monitoring in grain storage.

“bite” of soft drinks by stimulating the olfactory and taste nerves. Also, the carbonation contained in these drinks prevents mould growth and the growth of bacteria. In other instances, carbonation might even kill some bacteria, which is based on the amount of carbonation employed. Together with the acidity present in the beverage, the CO_2 content effectively preserves carbonated drinks for an extended period [72].

Inerting

Inerting the production of fruit juice with CO_2 helps minimize the reaction between the juice and the oxygen present in the containers. This reduces undesired fermentation later in the shelf life of the product thus prolonging the high quality sensory in the product [73].

STEEL INDUSTRY

With the increasing worry over climate change, manufacture of steel is now challenged to regulate carbon dioxide emission by providing a solution with minimal effect on its ability to perform its processes and without raising the cost. The largest industrial source of CO_2 emissions lies in both the iron and steel sectors, which are mainly because of the energy consumption required to make steel, the use of carbon based raw materials, and its production of 1,414 million tonnes and above of steel in the year 2010. The entire world steel production has been on a steady increase within the last 40 years and projected to continue increasing even more in the future, particularly in the developing economies. By providing all steel plants with electricity of hydroelectric generation stations, nuclear power generation stations or other environmentally friendly sources, they would greatly lower their indirect carbon dioxide emission as in Figure 44. The resulting shift-off would result in an almost zero carbon dioxide emissions of scrap-based electric arc furnace (EAF) mini-mills. Direct and indirect CO_2 emissions can be decreased with several technologies and processes that include:

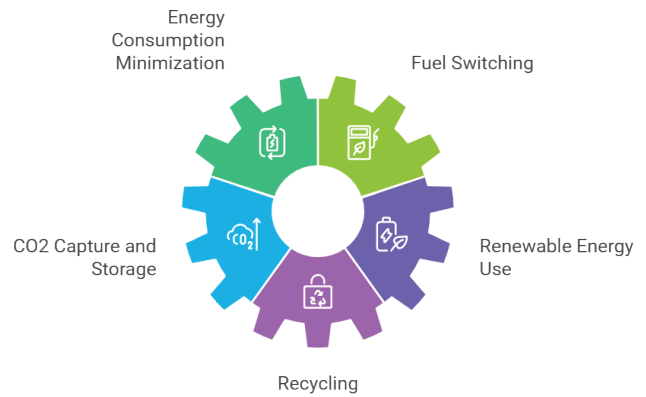


Figure 44. Strategies for reducing steel industry CO_2 emissions.

- Reduction of energy consumption, and enhance process efficiency.
- Replacing a fuel or an agent with a lower CO_2 .
- Sequestration of CO_2 and its storage in the ground.

In the future, indirect carbon dioxide emissions of the steel and iron industries are predicted to be reduced with the passage of time due to the creation of carbon sinks. Recycling scrap steel is also important towards saving energy and demanding carbon dioxide emissions [74].

Let's Capture The Future

Picarro, an Italian technology firm deals in advanced laser technology in gas network monitoring. Their creativity assists the network operators to detect gas leakages and minimise fugitive gas emissions. The laser system of Picarro makes it possible to detect areas much more accurately, in record time and covering much more area than conventional systems using cavity ring-down spectroscopy (CRDS).

The technology can be deployed in vehicles, boats, or backpacks, as shown in Figure 45. The detection equipment



Figure 45. Vehicles gas leak detector during the activities in COP 29 Baku, Azerbaijan.

includes an anemometer, GPS antenna, tablet, and smartphone. Its sensitivity is 1,000 times higher than that of conventional systems, allowing it to detect gas leaks from distances of about 150-200 meters. Notably, this technology does not require the vehicle to follow the route of the underground pipeline and can differentiate between methane (CH_4) and ethane (C_2H_6). The benefits of this surveying technology include Greater Safety, is a tenfold increase in network safety and sustainability, Lower Costs, its optimization of operating costs through the reduction of emergency calls, it also More Efficiency by Three times faster detection procedures, leading to greater network coverage, and will be More Reliability. Overall, Picarro's technology significantly advances gas network monitoring, making it safer and more efficient.

Another application is using drones to detect fugitive emissions through conducting methane detection and measurement campaigns using drones equipped with AUSEA (Airborne Ultra Lightweight Spectrometer for

Environmental Applications) technology, as shown in Figure 46. This technology, developed by TotalEnergies and its research and development partners, enables highly accurate detection and quantification of methane emissions from oil and gas facilities.

AUSEA features a miniaturized dual sensor mounted on a drone that can detect methane and carbon dioxide emissions while simultaneously identifying their sources. Developed by TotalEnergies, the French National Centre for Scientific Research (CNRS), and the University of Reims Champagne-Ardenne, AUSEA is now recognized as the most accurate technology in the world for detecting and measuring methane emissions.

Single-atom solution in capturing carbon and creating energy is presented in a recent study that presents, for the first time, the electrochemical conversion of carbamate species to methane (CH_4). In this study, they demonstrate that a single-atom nickel (Ni) catalyst, when dispersed on various conductive electrode materials, is capable of directly

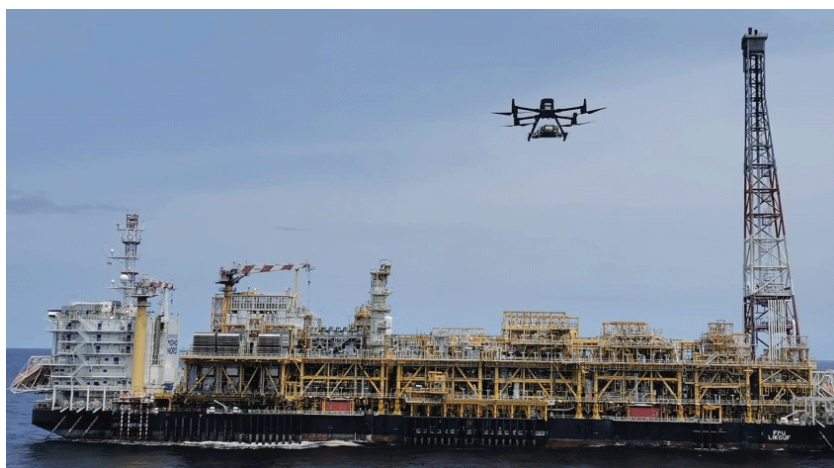


Figure 46. Drone leak detector to reducing methane emissions.

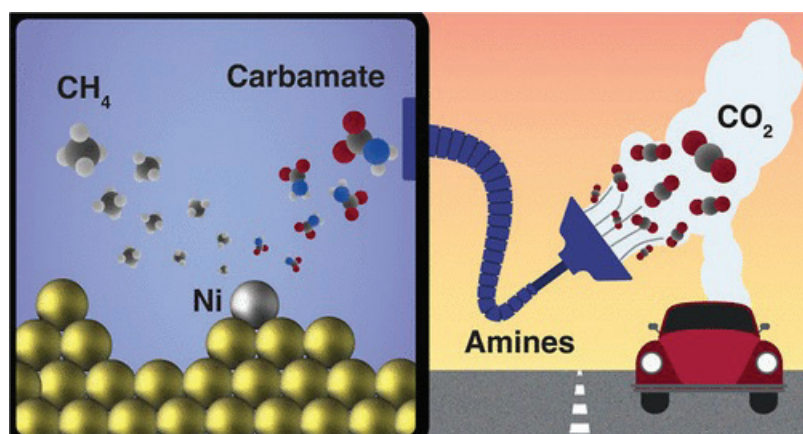


Figure 47. Convert the capture CO_2 using amines into methane by Ni catalyst.

reducing an amine capture solution to methane (CH₄). This catalyst exhibits a high selectivity for methane (CH₄) over other carbon-based products (Fig. 47) [75].

This integrated approach facilitates the conversion of carbon dioxide (CO₂) and the regeneration of the capture species in a single step, thereby completely eliminating the energy loss typically associated with the release of CO₂ from capture solutions. Despite the significance of completing the carbon (C) cycle, there are currently no known examples of an electrocatalyst that can directly convert the CO₂ capture species, carbamate, into a hydrocarbon. This study identifies a novel class of catalysts that can directly convert carbamate to hydrocarbons (CH) and offers significant mechanistic insights that may inform future applications involving the electrochemical conversion of CO₂ capture species into hydrocarbon products [75].

RESULTS AND DISCUSSION

It is necessary to promote the better quantification of CO₂ applications and their climate benefits. Exploring and facilitating early market opportunity to utilize CO₂ that is scalable, commercially viable, and potentially resulting in cuts in emissions must be a priority.

Although tremendous progress has over the past few years been achieved in carbon capture, utilisation, and storage (CCU/S) technologies and hydrogen energy production using methane, the listed several of questions in research will help to optimize the efficiency of industrial processes:

- **Hydrogen Production + Ccu/S Integration:**
 - Synergistic Optimization: Creating combined systems that receive maximum optimization in carbon capture and in hydrogen production to minimize energy losses and greatly enhance efficiency.
 - Co-product Utilization: The utilisation of by-products of each process, like carbon and value-added chemicals, to enhance the overall economic value.
- **More Efficient Carbon Capture Technologies:**
 - High-Performance Sorbents: Producing ultra-efficient and selective sorbents to capture CO₂ in industrial flue gases, particularly to difficult situations, such as steel and cement manufacturing.
 - Membrane-Based Separation: How can the performance and the life of membranes used in the separation of CO₂ be enhanced, especially in high-temperature and pressure setting.
 - Energy-Efficient Capture Processes: Advancing new methods to decrease energy usage related to carbon capture, including solvent regeneration and pressure swing adsorption.
- **Efficient Hydrogen Generation of Methane:**
 - Catalytic Processes: Hyperefficient and stable catalysts in other processes such as reforming of

methane and pyrolysis to enhance process efficiency and hike the hydrogen production.

- Designing Revolutionary Reactor Designs: Native reactor design: coming up with new reactor designs that promote efficiency and decrease emissions as a result of improved heat and mass transfer.
- Renewable Energy Integration: Investigating the possibility of integrating renewable energy, the source of solar and wind power, to serve as the needed energy source to produce hydrogen, which will decrease fossil fuel consumption.
- **Environmental Impact Assessment & Economic Feasibility:**
 - Life Cycle Assessment: Carrying out of thorough life cycle assessments to analyze the environmental and economic effects of various carbon capture and hydrogen generation technologies, including energy use aspect, carbon emissions and water use.
 - Cost-Benefit Analysis: Building strong cost-benefit analyses to determine the most cost-effective and eco-friendly solutions to industrial processes.
- **Policy And Regulatory Frameworks:**
 - Incentive Mechanisms: Delineation into effective policies and incentives to spur adaptation of CCU/S and hydrogen technology, like carbon tax credential, carbon certification, and carbon pricing/trading.
 - Standardization and Certification: Developing universal guidelines and certification of carbon capture and hydrogen technologies that achieve quality, safety and environment friendliness.

These gaps in research can be bridged to potentially realize a high degree of efficiency and sustainability of the industrial process, leading to a low-carbon future.

Therefore, it is important to support research and development for future applications of CO₂ that could contribute to a CO₂-neutral economy. A legislative and regulatory framework for trading hydrogen and carbon in various new uses and applications should also be established.

CONCLUSION

This paper reviews and analyzes the potential and the challenges of carbon capture and storage, hydrogen energy storage technologies, and their energy efficiency in various applications, as well as the benefits of properly and sustainably exploiting both methane and carbon emissions.

The most common method for producing hydrogen from methane is steam reforming, which has an energy efficiency of 65% to 75%. This process can produce carbon dioxide as a byproduct, which can be integrated into new services and products aimed at achieving sustainable development goals. Although methane pyrolysis is still in the experimental phase and has an estimated energy efficiency of about 58%, it marks a significant advancement in

the production of clean hydrogen and solid carbon for various applications, all while generating minimal emissions.

Hydrogen is an emerging energy carrier that exists naturally and can be produced in various forms for electricity generation and as a key raw material in several important industries. Additionally, hydrogen serves as a clean fuel for transportation, much like its historical use in spacecraft.

One of the primary sources of hydrogen that contributes to the reduction of carbon emissions in the atmosphere is methane. Hydrogen can be extracted from methane through various chemical reaction mechanisms, enabling its use in a range of applications.

Carbon dioxide can facilitate new industrial development in a sustainable manner, contributing to the production of low-emission concrete, advancements in the chemical industry, and innovations in the food industry. For example, it can play a role in enzyme immobilization for food quality control and in protein precipitation processes, as well as in the production of soft drinks.

ABBREVIATIONS

ATAG	Air Transport Action Group
ATR	Auto-Thermal Reform
BEVs	Battery Electric Vehicles
CDR	Carbon Direct Removal
CHP	Combined Heat & Power
CCS	Carbon Capture & Storage
CCU	Carbon Capture & Utilisation
EAF	Electric Arc Furnace
ETC	Energy Transformation Commissions
EU	European Union
FCs	Fuel Cells
GHGs	Greenhouse Gases
GT	Giga Tone
HFCVs	Hydrogen Fuel Cell Vehicles
HSE	Health, Safety & Environment
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Analysis
LH2	Liquid Hydrogen
LNG	Liquified Natural Gas
LOHCs	Liquid Organic Hydrogen Carriers
LSMGO	Low Sulfur Marine Gas Oil
MMTCO ₂	Million Tons of Carbon Dioxide
NZE	Net-Zero Emissions
O&G	Oil & Gas
PEMFC	Polymer Electrolyte Membrane Fuel Cell
SMR	Steam Methane Reform
SOFCs	Solid Oxide Fuel Cells

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AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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