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CO2 Conversion Based on Plasma Technologies: Review

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***Abstract*— The increasing concentration of carbon dioxide gas in the world has led to exploring solutions and alternatives to reduce these concentrations or benefit from carbon dioxide gas and use it as an environmentally friendly fuel and in other applications. There are many ways to decompose gas into oxygen, carbon, or carbon monoxide, including chemical and thermal methods. This can also be done using plasma techniques. A review of the literature related to plasma-based carbon dioxide dissociation will be presented. It also describes some different types of plasma, in addition to explaining the results of recent scientific research in this regard. The results of recent conclusions have shown that through plasma technology, high energy efficiency can be achieved, which indicates the efficiency of plasma in its use in converting carbon dioxide gas.**

Keywords— CO2 Conversion; plasma; CO2 Dismantling; Microwave (MW); Dielectric Barrier Discharge (DBD).

I. INTRODUCTION

Carbon dioxide (CO2) which is a basic element in the Earth's atmosphere, is useful in balancing the environment. Carbon dioxide levels have gone up due to activities such as the use of fossil fuels deforestation and different industrial practices since the industrial revolution. [1]. Increasing amounts of CO2 are primarily responsible for global warming which causes many environmental problems. Recognizing and dealing with the effects of this growth in carbon dioxide emissions on Earth is of great importance as they are increasing globally. [2]

The existing state of anthropogenic pollution and the careless release of greenhouse gases into the atmosphere have the potential to worsen desertification, ocean acidification, global warming, and weather variability. However, some of the immediate effects of climate change are health issues, migration, increased economic damage, rising sea levels, and strong storms that harm coastal communities [3]. Table 1 shows the problems of increasing the percentage of carbon dioxide gas.

TABLE I. Problems Resulting from Increasing CO2 Levels[4]

Problem	Description	Impact
Climate Change and Global Warming	CO2 traps heat in the atmosphere, causing global temperatures to rise.	More frequent and severe weather events, melting ice caps, and rising sea levels.
Ocean Acidification	CO2 is absorbed by oceans, making them more acidic.	Dissolution of calcium carbonate shells of marine organisms, disrupting marine ecosystems.
Health Impacts	Increased CO2 levels can exacerbate respiratory conditions and cognitive function.	Aggravated asthma, reduced cognitive function, heat-related illnesses, and spread of diseases.
Agricultural Impact	Climate change affects temperature and precipitation patterns.	Droughts, floods, reduced crop yields, lower nutritional value of crops.
Biodiversity Loss	Climate change and ocean acidification threaten various species.	Habitat loss, increased risk of extinction, and disruption of ecosystems and services.

II. CO2 REDUCTION TECHNIQUES

There are many techniques to reduce or limit the percentage of carbon dioxide gas by fragmenting it and dividing it into its basic components, such as Photovoltaic Industry Association [5], photocatalysis, the electrochemical method, the thermochemical method, plasma, and others [6]. Table 2 shows some of the carbon dioxide reduction techniques.

TABLE II. Reduction Techniques for CO2 gas.

Techniques	Method
Photocatalytic Reduction	uses light, usually ultraviolet or visible light, to initiate a chemical reaction that transforms CO_2 into alternative substances. The reaction is facilitated by the titanium dioxide photocatalyst. This way of reducing carbon dioxide mimics photosynthesis and can potentially serve as an atmospheric carbon capture technique that converts it to other compounds like carbohydrates.[7]
Electrochemical Reduction	In this process, CO_2 is reduced to other products using electrical energy. Electrochemical cells or reactors use electrodes to drive the reaction, often producing compounds like carbon monoxide, methane, or ethylene. This method can be integrated with renewable energy sources to create a sustainable CO_2 reduction process.[8]
Thermochemical Reduction	This method involves using high temperatures to drive the chemical reduction of CO_2. Typically, it employs a thermal catalyst to facilitate reactions at elevated temperatures, converting CO_2 into useful chemicals or fuels. This approach is energy-intensive but can be efficient for large-scale applications.[9]

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Biochemical Reduction	In this technique, biological systems or enzymes are used to reduce carbon dioxide. This can include microorganisms or enzymes that catalyze the conversion of carbon dioxide into useful products, often through metabolic pathways similar to those found in nature.[10]
Plasma Reduction	Plasma technology involves ionizing gas to form a high-energy plasma state. In carbon dioxide reduction, plasma is used to catalyze chemical reactions that convert carbon dioxide into other compounds. This method is classified as thermochemical due to the high temperatures and energy used to generate the plasma. It has many types depending on the type of source used to generate plasma.[11]

III. PLASMA-ASSISTED CO2 DISMANTLING

Irving Langmuir was the one who originally used the word "plasma" (1928). Since at least one electron is free to form positively charged ions, plasma is an ionized gas [12]. In reality, there are several levels of ionization in plasma, ranging from 100% completely ionized gases to partially ionized gases. In addition to a wide variety of ions, both positive and negative, plasma also contains a huge number of neutral species, such as diverse atoms, molecules, radicals, and excited species. The latter may result in light emission, among other things. The fact that these species may interact with one another is even more significant since it turns plasma into a complex and extremely reactive chemical cocktail that has a wide range of possible uses. Indeed, because of their light-emitting properties, plasmas are already used in a variety of applications in the materials science field (such as coating deposition, surface modification, and nanomaterial fabrication) and the microelectronics industry (for the manufacturing of microchips). They are also used in many developing environmental and even medical fields (such as sterilization, wound treatment, and even cancer treatment). However, used in the conversion of CO2 into fuels and chemicals with added value. Because matter turns into solid, liquid, (neutral) gas, and eventually an ionized gas or plasma as the temperature rises. Over 99% of the visible matter in the universe is in the plasma state, mostly due to interstellar matter and stars, despite the idea of plasma being less understood than the other states of matter [13].

Ionized gas is known as plasma, sometimes called the fourth state of matter. Because of their high energy, at least some electrons in ionized gases are not further bonded to atoms or molecules. Because they may attain higher energy densities than traditional processes and include a high concentration of reactive species such electrons, ions, radicals, and excited species, plasmas are particularly appealing for conversion processes. Additionally, because plasmas may be controlled far from thermodynamic equilibrium, these reactive species can already be given at low bulk temperatures [14]. Figure 1 shows the plasma types and the most famous technologies.

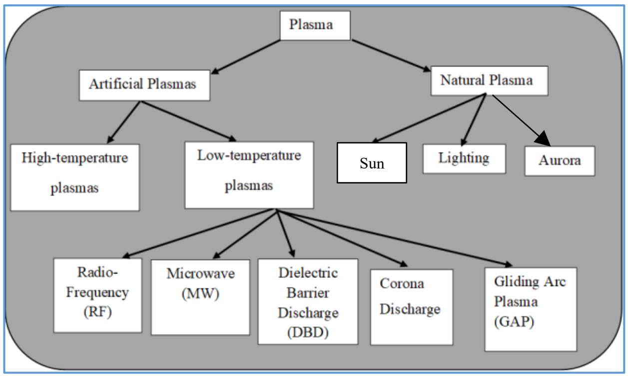

Fig.1. The most famous types of plasma

Two categories of artificial plasmas may be identified, those important to technical applications. One type of plasma is employed in nuclear fusion processes; these are high-temperature plasmas, which are typically completely ionized. Conversely, low-temperature plasmas, which are often referred to as gas discharges, are typically characterized by a low level of ionization. Whether or whether the latter, low-temperature plasmas, are in a (local) thermodynamic equilibrium (LTE), they can be further separated. The energy distribution (or temperature) of the different species that make up a plasma may vary from one another. In such a scenario, the plasma is considered non-LTE or non-thermal plasma and is considered to be distant from LTE. On the other hand, the plasma is categorized as thermal or LTE plasma if LTE exists. The region that lies between thermal and non-thermal plasmas can occasionally be classified as a different kind of plasma, known as warm plasma. These characteristics of this kind of plasma high degree of non-equilibrium and a comparatively high energy density—make it ideal for operations involving the conversion of gases [15].

In general, when a neutral gas is given enough energy, plasmas can form. This can be accomplished, for instance, via adiabatic compression or heat energy from exothermic processes. In technological applications, an electric field is primarily used for the creation and maintenance of low-temperature plasmas. Free charge carriers are accelerated by the electric field, and collisions with other particles result in the loss of existing charge carriers or the production of new ones. In this technique, a stable, steady-state plasma may be established under certain working parameters [16].

Techniques to reduce the amount of carbon dioxide gas in the atmosphere have been proposed, including high- or low-pressure microwave plasma, gliding arc reactors, dielectric barrier discharge (DBD) reactors, ns-pulses, and arc discharge. Globally, the usage of technologies based on plasma to convert CO2 is rapidly growing [17]. Plasma technology offers distinct viewpoints because of its ability to carry out chemical reactions in gases at normal temperature and pressure. It is essential to comprehend the fundamentals of CO2 conversion. The most popular type of plasma reactor for decomposing CO2 is the Microwave(MW) and dielectric barrier discharge (DBD) reactor. An electric potential difference between two electrodes at least one of which is shielded by a dielectric has been used in a DBD reactor to produce plasma. Among the many benefits of the DBD reactor for CO2 breakdown are its capacity to operate at atmospheric pressure, its straightforward design that simplifies industrial applications, and above all its fast on/off switching [18]. Table 3 shows some plasma technologies and the principles of each one.

TABLE III. The Principle of most plasma technologies

Plasma Technologies	Principle
Radio-Frequency (RF) Plasma	Utilizes radio-frequency energy (typically 13.56 MHz) to generate plasma. RF energy is coupled to the gas through capacitive or inductive methods. [19]
Microwave (MW) Plasma	Uses microwave energy to ionize gas and generate plasma. Typically operates at frequencies of 2.45 GHz or 915 MHz.[20]
Dielectric Barrier Discharge (DBD)	Utilizes alternating current (AC) or pulsed voltage to generate a plasma between two electrodes separated by a dielectric barrier. [17]
Corona Discharge	Uses a high voltage to ionize gas around a conductor, creating a corona discharge. It occurs at points where the electric field is highly concentrated. [21]
Gliding Arc Plasma (GA)	Creates plasma by an arc that glides between two electrodes under the influence of gas flow. The arc glides along the electrodes and elongates until it extinguishes and reignites.[22]

As a result, there is a great deal of optimism that employing this technology during the height of power generation will supply the necessary resources for the network to store renewable energy.

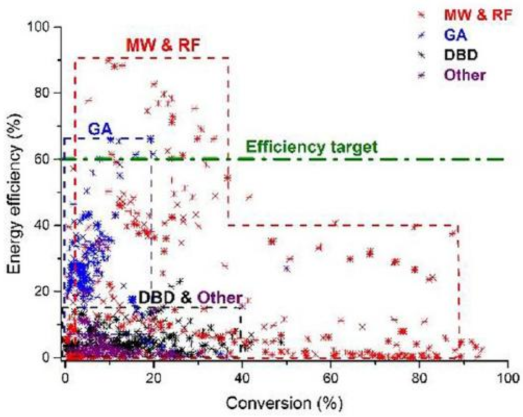

Fig.2. conversion and energy efficiency of plasma types reactors [23]

Given the need to maintain or even reduce the carbon dioxide content in the atmosphere, the carbon dioxide conversion zone has now become an important topic. Research on CO2 conversion technologies, such as thermochemical, photochemical, electrochemical, and biochemical conversion processes, is very extensive. However, none of the emerging technologies appear to be better. However, given the favorable conditions mentioned above, the use of plasma reactors seems promising. Since the high-energy electrons in carbon dioxide make it reactive, in theory, there would be no need to heat it to extremely high temperatures. Furthermore, since plasma reactors are electrically powered, they are suitable for extreme shaving and grid stabilization applications because they are easy to operate and provide a very flexible mode of operation [24].

IV. LITERARY REVIEWS

Viegas et al. [25], offer profound insights into the contraction dynamics of microwave plasmas tailored for CO2 conversion. Employing sophisticated plasma chemistry modeling, their work delves into the intricacies of plasma behavior, shedding light on the fundamental processes dictating the evolution of these dynamic systems. This foundational exploration serves as a cornerstone for subsequent research endeavors, providing a basis for understanding the complexities inherent in CO2 plasma reactions.

Further enriching our understanding of the vibrational non-equilibrium time window in plasma activation of N2, CH4, and CO2, Van de Steeg et al. [26] offer a nuanced perspective on the temporal aspects of plasma reactions.

Investigation of thermal dissociation in CO2 microwave discharges and determination of mode-specific heating dynamics in pulsed microwave CO2 plasmas, respectively. Van den Bekrom et al. [27]

Mercer et al. [28] delve into post-plasma quenching strategies, proposing innovative approaches to enhance conversion and energy efficiency in CO2 microwave plasma systems.

D'Isa et al. [29] delve into the practical realm by offering a detailed performance analysis of a microwave plasma torch configured for CO2 decomposition in a gas swirl configuration. Providing valuable insights for designing and optimizing microwave plasma systems for CO2 reactions This practical assessment bridges the gap between theoretical understanding and real-world applicability.

A. Hecimovic et al. [30] compare atmospheric pressure microwave-induced CO2 plasma splitting with electrochemical CO2 conversion using low-temperature and high-temperature electrolysis. Key features include large conversion rates (up to 56%) and moderate energy efficiencies (up to 27%). The comparison reveals that plasma conversion technology is in the ballpark with other electrochemical technologies in terms of electric power consumption. The technology is particularly suitable for intermittent renewable energy sources.

The study by Y. Uytdenhouwen, S et al. [31] investigated the effect of gap size reduction and packing materials on CO2 dissociation conversion in a packed DBD micro-plasma reactor. The results show that reducing the discharge gap increases the conversion but reduces the energy efficiency. Adding fill material increases conversion but depends on the composition of the material, gap, and ball size. Maximum conversions of 50-55% are achieved for long residence periods, indicating an equilibrium in the CO dissociation and recombination reactions.

Ray, D., Saha, R., & Ch, S. [32] study on carbon dioxide partial reduction in a packed bed dielectric barrier discharge reactor aimed to understand the influence of diluent gas on CO2 splitting, with Ar gas showing the best decomposition efficiency.

Yukio Hayakawa, Primas Emeraldi, et al. [33] examined the effect of micro-gap discharge and pulsed energy on CO2 conversion performance in pure CO2 splitting processes. The results showed that the gas flow rate significantly affected the CO2 conversion and flow density, while the discharge power significantly affected the energy efficiency and discharge system. Table 4 shows some articles that used plasma techniques to split carbon dioxide gas.

TABLE IV. Plasma technology type and reactor design

Reference NO.	Technology type	Plasma reactor design
[25]	Chemistry plasma with MW	-------
[26]	Chemistry technique with MW plasma	Fig.3
[27]	Thermal dissociation in CO2 microwave	Fig. 4
[28]	Post-plasma quenching strategies	Fig.5
[29]	Microwave plasma torch	Fig.6
[30]	Electrochemical CO2 reduction with MW plasma	Fig.7
[31]	Packed bed DBD microplasma reactor for CO2 dissociation	Fig.8
[32]	DBD Plasma with Influence of Diluent Gases	Fig.9
[33]	Dielectric Barrier Discharge Plasma in Catalysis	Fig.10

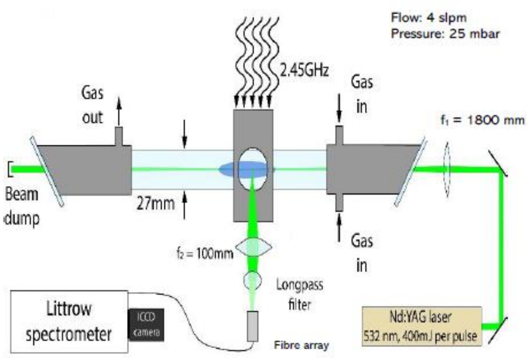

Fig.3. Experimental setup and diagnostic arrangement

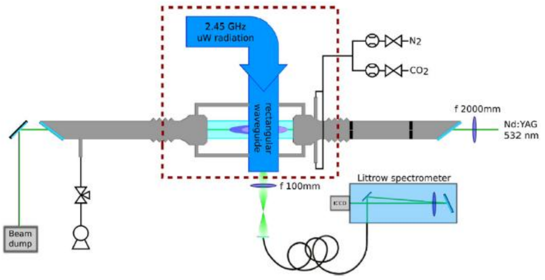

Fig.4. Schematic of the pulsed microwave plasma experiment diagnosed with laser scattering. A solid-state microwave source produces plasma in the gas flow cell. Frequency-doubled Nd: YAG laser light is focused in the center of the discharge.

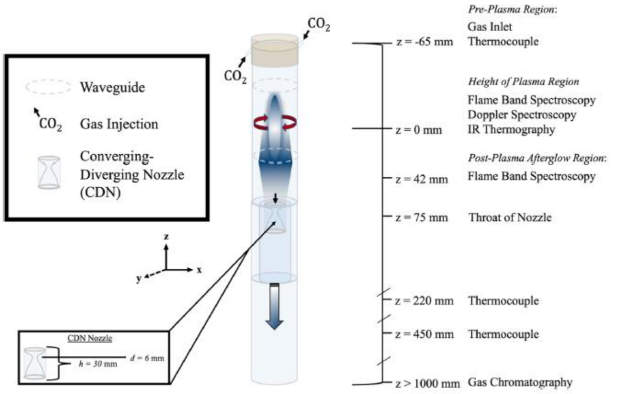

Fig.5. Setup overview with relative distances of the diagnostics from the plasma, as well as the placement of the CDN from the plasma region.

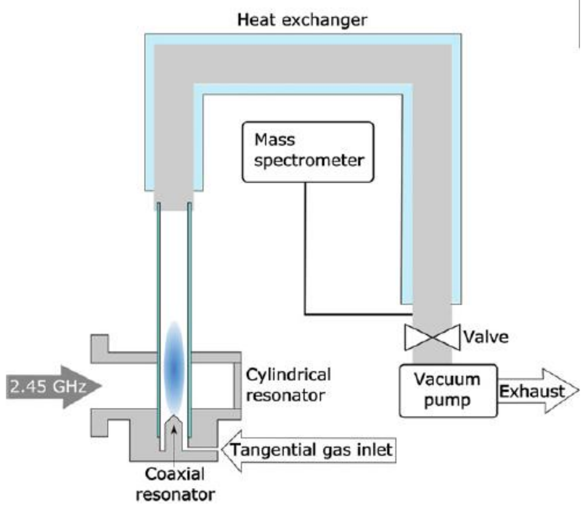

Fig.6. Schematic of the plasma torch and its exhaust system.

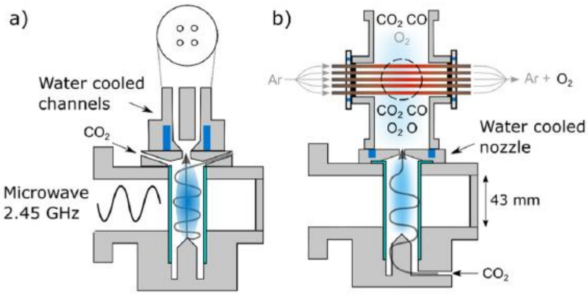

Fig.7. Schematic representation of the atmospheric pressure microwave plasma torch with a) four cooled effluent channels (a cross-section of the channels is shown above the schematic), and b) nozzle and oxygen separation membranes. Microwave power levels up to 3 kW, and CO2 flows in the range 3.7–20 slm are used.

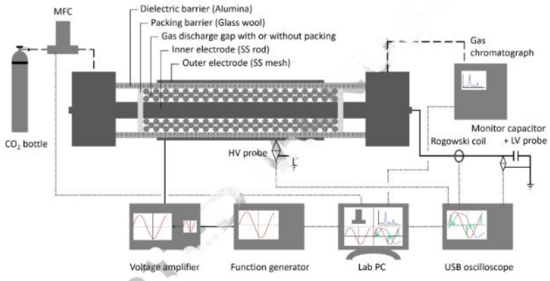

Fig.8. Packed bed DBD reactor

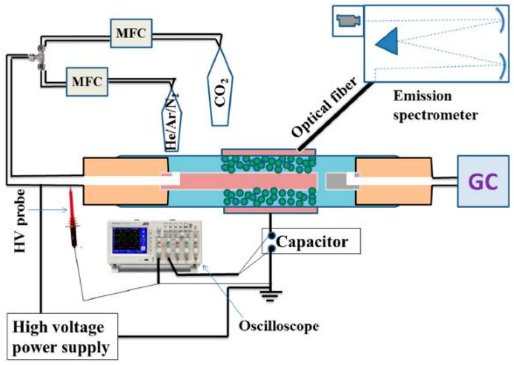

Fig.9. Simplified diagram of experimental setup

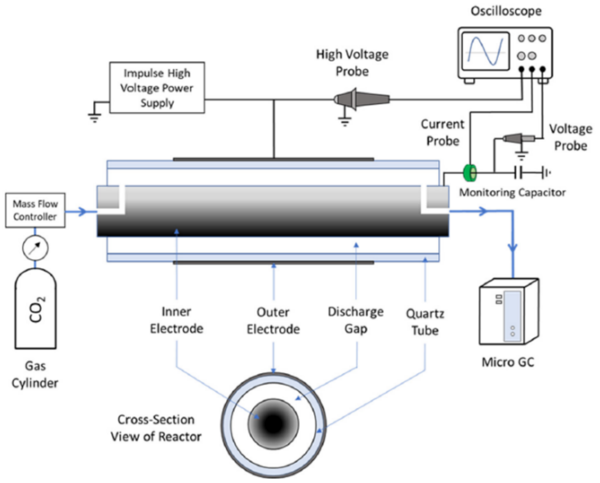

Fig.10. Diagram of reaction experimental device

The figures below illustrate the emission spectra of converted CO2 gas for two of the most popular plasma technologies.

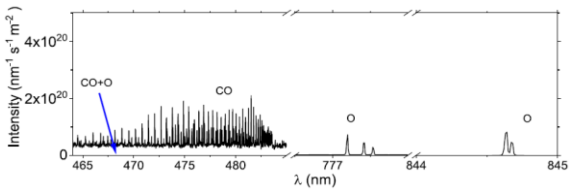

Fig.11. emission spectra of converted CO2 gas of 2.45 GHz microwave plasma[29]

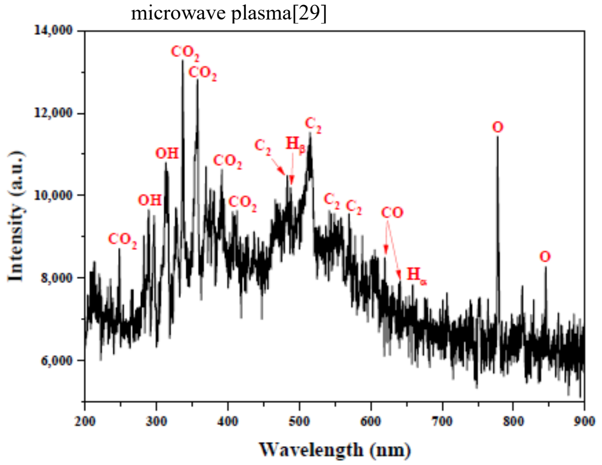

Fig.12. Emission spectra of converted CO2 gas of BDB reactor [17]

This multifaceted body of literature collectively contributes to a comprehensive understanding of the multiphysics aspects governing microwave CO2 plasma reactions within cylinder domains. The amalgamation of theoretical frameworks, experimental insights, and practical considerations encapsulates the richness and dynamism of this evolving field, offering a robust foundation for future exploration and innovation.

V. USES OF CARBON DIOXIDE GAS AFTER SPLITTING

Carbon dioxide gas is used after being analyzed in one of the previous methods into carbon monoxide, carbon and oxygen in the manufacture of fuel, as it is considered a renewable energy through the use of carbon monoxide or through its use with methane to produce products of high industrial value, as shown in Table 5.

TABLE V. Common uses of carbon dioxide gas

References No.	Methodology
[34]	One possible technique to carry out the operations is the conversion of photocatalysis. Toxic CO has been eliminated for several use cases by photo-catalytically oxidizing it with O2 or NO to environmentally benign CO2. Meanwhile, it has been demonstrated that CO can be effectively converted into fuels with higher energy content by photocatalytic reactions between CO and H2O and CO and H2.
[35]	Producing fuels and chemicals by converting CO2/CO2 into liquid products using renewable electricity; nevertheless, more progress in the understanding, development, and device integration of electrocatalysts is needed.
[36]	Using CO2 as a building component could be an intriguing way to create synthetic processes that use less energy and emissions. This research initially examines the general characteristics of carbon dioxide and how it interacts with metal centers. Next, it talks about how carbon dioxide can be used as a raw material to create compounds like carboxylates, carbonates, and carbamates. The prerequisites for its execution are discussed, and the use of CO2 as a carbon source for the production of fuels and other C1 molecules like methanol and formic acid is also described.
[37]	This manuscript contains the literature on the direct conversion of methane and carbon dioxide into higher-value products. By decomposing carbon dioxide gas and using carbon and carbon monoxide

Bart and Enton et al.[38] have reviewed the performance measurement formulas, noting the frequent inaccuracies and inconsistencies presented to anyone who wants a solid understanding of what is sometimes called climate change. The focus on pure CO2 splitting, dry methane reforming, and CO2 hydrogenation is very useful. It points out the crucial but often overlooked point of many reactions, which is what happens to their inherent speed of change (i.e., time effects). In addition, the use of numerical examples to explore what extreme differences and discrepancies might look like is provided by the authors. Guidance on correction and best practices is provided to ensure more consistent calculations.

VI. CONCLUSION

The rate of carbon dioxide emission into the atmosphere is constantly increasing and is the main factor in the phenomenon of global warming. Reduction processes and techniques can help reduce the percentage of this gas and use it in the production of industrially valuable compounds, such as its use in the manufacture of environmentally friendly fuels. The use of plasma technologies is one of the most famous technologies used, but it needs more progress and development in terms of energy use and efficiency, as well as conversion efficiency. Some technologies also require high energy, so the use of renewable energy sources is the best proposal and alternative to carbon materials. Scientists' efforts have been directed toward working on manufacturing a reactor that overcomes the current problems, which are reactor instability, high capacity, and necessary financial costs. Scientists and engineers seek to find and manufacture reactors with high stability, lower capacity, and reasonable financial costs. As a result, research is directed towards MW and RF. Overcoming these challenges has great positive results in reducing carbon dioxide emissions and producing useful and environmentally friendly fuel.

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