Advancements in the Application of CO$_2$ Capture and Utilization Technologies—A Comprehensive Review

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Abstract: Addressing escalating energy demands and greenhouse gas emissions in the oil and gas industry has driven extensive efforts in carbon capture and utilization (CCU), focusing on power plants and industrial facilities. However, utilizing CO$_2$ as a raw material to produce valuable chemicals, materials, and fuels for transportation may offer a more sustainable and long-term solution than sequestration alone. This approach also presents promising alternatives to traditional chemical feedstock in industries such as fine chemicals, pharmaceuticals, and polymers. This review comprehensively outlines the current state of CO$_2$ capture technologies, exploring the associated challenges and opportunities regarding their efficiency and economic feasibility. Specifically, it examines the potential of technologies such as chemical looping, membrane separation, and adsorption processes, which are advancing the frontiers of CO$_2$ capture by enhancing efficiency and reducing costs. Additionally, it explores the various methods of CO$_2$ utilization, highlighting the potential benefits and applications. These methods hold potential for producing high-value chemicals and materials, offering new pathways for industries to reduce their carbon footprint. The integration of CO$_2$ capture and utilization is also examined, emphasizing its potential as a cost-effective and efficient approach that mitigates climate change while converting CO$_2$ into a valuable resource. Finally, the review outlines the challenges in designing, developing, and scaling up CO$_2$ capture and utilization processes, providing a comprehensive perspective on the technical and economic challenges that need to be addressed. It provides a roadmap for technologies, suggesting that their successful deployment could result in significant environmental benefits and encourage innovation in sustainable practices within the energy and chemical sectors.

Keywords: CO$_2$ capture & utilization; CO$_2$ emissions; flue gas; industrial fuels; petrochemicals

1. Introduction

For the next 50 years, fossil fuels are expected to remain the primary energy source despite the significant impact of CO$_2$ emissions on climate change [1]. Addressing this issue requires the development and implementation of net-zero carbon technologies. A consensus on the need for substantial reductions in CO$_2$ emissions across all industries and achieving net greenhouse gas neutrality was reached at the 2015 UN Climate Change conference in Paris. Achieving net-zero carbon involves balancing anthropogenic emissions from industrial sources with continuous removal from sinks over the next 50 years [1–3].

On the other hand, the projected significant increase in global pollution is expected to drive a surge in energy demand in the coming decades. This necessitates the emergence of efficient renewable energy alternatives. One promising solution to the challenges of energy supply and emissions is the utilization of captured carbon dioxide as a valuable industrial feedstock for producing various fuels and chemicals, creating added value [4]. Concepts of carbon capture and utilization play a crucial role in addressing climate change and carbon management. Carbon capture and storage (CCS) technologies involve extracting and compressing carbon dioxide from gas streams to its supercritical state before sequestering it in

geological formations such as oceans or depleted hydrocarbon formations. Despite government incentives, regulatory policies, and promises of mitigating large volumes of CO_2, the high cost of capturing and compressing CO_2 has limited the large-scale deployment of CCS [5,6].

An effective method of CO_2 capture is post-combustion capture, which is widely used in industrial settings such as power plants [7]. This method uses chemical solvents such as monoethanolamide (MEA) to efficiently extract CO_2 from flue gases, making it suitable for upgrading existing infrastructure and achieving high capture rates [8]. Another method, pre-combustion capture, is integrated into processes such as reforming natural gas and gasification of coal to remove the CO_2 from fuel before combustion. This process not only reduces CO_2 emissions but also produces hydrogen, a clean fuel alternative [9].

Fischer–Tropsch synthesis (FTS) is a key technology in the CCU landscape, offering an adaptable approach to converting CO_2 into various valuable hydrocarbon fuels and chemicals. By using catalysts such as iron and cobalt, FTS efficiently produces synthetic fuels such as diesel and jet fuel, which are compatible with the existing fuel infrastructure and distribution networks. This dual benefit of reducing CO_2 emissions while generating sustainable fuels emphasizes the importance of FTS in the current and future energy landscape [10,11]. FTS extends beyond thermal applications into electrocatalytic and photocatalytic conversion. Electrocatalytic conversion allows the direct conversion of CO_2 into hydrocarbons under ambient conditions using renewable electrical energy. This makes it a promising avenue for integration with sustainable energy systems [12].

Photocatalytic processes, leveraging solar energy, provide another innovative approach by using light to drive the reduction of CO_2 into fuels and chemicals, presenting significant potential for reducing greenhouse gas emissions and producing renewable energy [13]. Furthermore, advancements in electrochemical reduction have enabled the conversion of CO_2 into valuable chemicals such as methanol and formic acid, leveraging renewable energy to promote a circular carbon economy [8]. Innovative approaches such as mineral carbonation and biological conversion are also being explored for their potential to permanently sequester CO_2 and produce useful products such as building materials and biofuels. These methods highlight the diverse practical applications of CO_2 management technologies and their role in sustainable development. By converting CO_2 from a waste product into valuable resources, these advanced CCU technologies support climate goals and promote economic growth through environmentally responsible practices [8,10].

Capturing and compressing CO_2 accounts for approximately 75% of the total cost of CCS [5]. Although the use of CCS technologies can reduce emissions from power generation industries and other industrial applications, their widespread implementation has been hindered by the associated high cost. A 2013 report from the International Energy Agency (IEA) estimated the implementation of about 3000 CCS projects globally [14], with the capacity to store over 7000 million tons of CO_2 annually [15].

More recently, attention has shifted toward carbon capture and utilization technologies as a more sustainable alternative to the permanent sequestration of CO_2 [16]. Converting captured CO_2 into valuable industrial and petrochemical products has emerged as a viable option. In contrast to traditional petrochemical feedstocks, carbon capture and utilization (CCU) technologies treat captured carbon dioxide as a renewable source [17]. Although the thermodynamic stability of CO_2 poses challenges in its conversion and use in chemical reactions, the benefits of CCU over CCS cannot be overlooked [18].

This study aimed to comprehensively review the latest advancements in carbon capture and utilization technologies, with a significant focus on carbon management. The review also provides a broad overview of the expected opportunities and challenges in the future. By examining the technological advancements, potential benefits, and associated challenges, this research offers valuable insights into the ongoing discourse on sustainable utilization and management of carbon.

2. Available Options for CO$_2$ Capture: Analyzing the Challenges and Opportunities

Reducing the carbon intensity of power generation and CO$_2$ capture technologies involves post-combustion and pre-combustion processes. Post-combustion carbon capture involves removing carbon dioxide from the flue gas streams, while pre-combustion focuses on developing less carbon-intensive combustion methods. Pre-combustion systems include the integrated gasification combined cycle (IGCC) and oxyfuel combustion, which uses purified oxygen as fuel [19]. Recent techno-economic analyses have revealed that to significantly reduce electrical costs and increase the efficiency of combustion, energy-intensive CO$_2$ capture technologies need to be utilized.

The choice of capture technology for a particular industry depends on the source of carbon dioxide and the industrial process involved. The source of CO$_2$ generation plays a critical role in determining the energy costs of CO$_2$ capture. For example, petrochemical production plants produce highly concentrated CO$_2$ emissions, while power plants produce lower concentrations, requiring more energy for recovery [20]. However, power plants are the largest source of CO$_2$ emissions, posing a significant challenge for the energy sector. Additionally, supercritical carbon dioxide combustion processes that utilize re-generated carbon dioxide and operate in its supercritical state are effective in addressing anthropogenic emissions.

Using supercritical CO$_2$ as an operating fluid in a power cycle has significantly increased the energy efficiency of plants in various dynamic contexts compared with the traditional steam cycle. Studies have shown that using carbon dioxide as a working fluid instead of oil improves steam turbines' efficiency [21]. However, this method requires purified oxygen for its use. Furthermore, liquid and gaseous CO$_2$ recirculation are two possible routes. Liquid CO$_2$ undergoes cryogenic treatment, and approximately 45% of global CO$_2$ emissions are attributed to power plants, demonstrating substantial potential for CCU and CCS alternatives to capture CO$_2$. Commercial implementation of CO$_2$ capture technologies, specifically post-combustion technologies, has a greater economic impact on reducing the cost of CO$_2$ capture compared with other options [22]. In the best-case scenario, implementing advanced post-combustion capture technologies in a newly developed power plant would cost an estimated USD 56 per ton, resulting in a 62% energy penalty for the plant. Carbon technologies are already commercially deployed in the natural gas and chemical industries [17].

SaskPower's Boundary Dam 110 MW power station has successfully demonstrated industrial-scale capture of post-combustion CO$_2$ from coal-fired flue gas [23]. Figure 1 presents the various capture processes studied in both the industry and academia over the last few decades. These processes are further detailed in the next section of this study.

2.1. CO$_2$ Capture Technologies: Absorption

Capturing CO$_2$ by absorption is the most widely used separation technique in the petrochemical industry. It has been extensively used for pre-combustion and post-combustion capture. A well-recognized method of post-combustion CO$_2$ capture used in various industries involves the chemical absorption of aqueous ammonia and amine-based solvents. Commercial physical absorption technologies such as Rectisol, Fluor, Purisol, and Selexol are available for petrochemical and industrial applications [24–27].

Nevertheless, their limited working capacity is the main hindrance to their widespread implementation in CO$_2$ capture processes. The significant energy demand for solvent regeneration results in high energy penalties associated with absorption processes, despite their efficiency in CO$_2$ capture. While heat integration helps lower the energy consumption in certain industries such as power plants, achieving reduced energy consumption in other industries such as cement, iron, or steel remains a challenge [28–31]. Additionally, operational constraints such as corrosion and a high makeup volume of water pose serious obstacles.

Chemical absorption typically relies on thermal swing regeneration. Therefore, the development of effective absorption-based CO$_2$ capture processes depends on selecting solvents with optimal thermal and physical features. Chemical solvents such as piperazine

(PZ) and its byproducts are preferred due to their low chemical reactivity, fast reaction kinetics, and, primarily, low regeneration energy [32]. Another approach to enhance the functionality of ionic liquids (ILs) is to incorporate functional groups such as carboxylate anions, amine, and amino acid groups. This could lead to the use of ILs as solvents for CO_2 absorption [4,33].
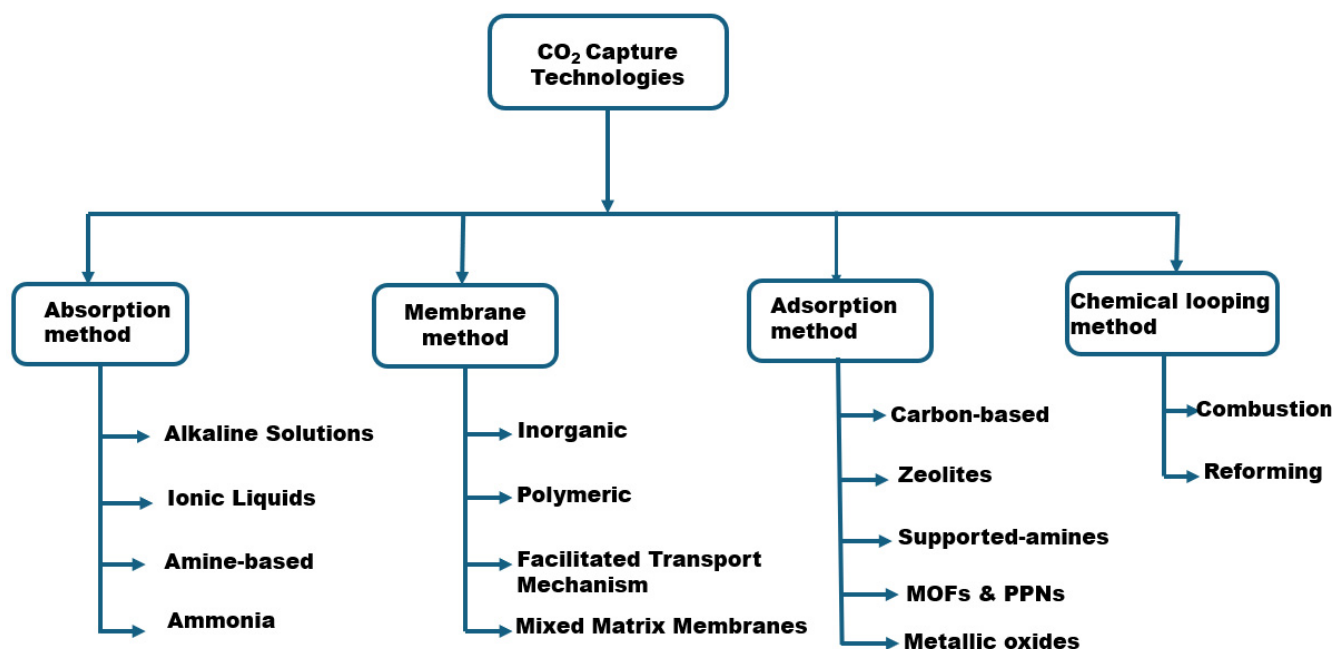

Figure 1. Different capture processes studied in both the industry and academia.

An important factor to consider is the balance between reaction kinetics and the heat generated during the reaction process. Using thermally stable solvents has significantly improved the separation processes, and solvents with an absorption heat greater than 60 KJ/mole are more effective in reducing energy consumption during chemical absorption. The stability of chemical solvents is often compromised by poisoned impurities, primarily found in the flue gas and other effluent streams [5]. Therefore, resistance to oxidation of the solvent and tolerance of impurities are significant performance indicators when developing new solvents for CO_2 absorption technologies [34].

Improvements to the process are equally critical for the scalability of the next generation of absorption technology, along with advances in the development of materials and selection of energy-efficient solvents. Consequently, emerging absorption technologies with enhanced processing configurations that offer effective heat integration strategies could provide innovative CO_2 capture solutions. Some of these heat integration strategies include intercooled absorbers and inter-heated strippers.

2.2. CO_2 Capture Technologies: Membrane Separation Processes

The use of membranes for gas separation is seen as an eco-friendlier and more energy-efficient technique compared with other methods. A pressure gradient across the membrane drives the permeation of CO_2 in membrane separation as a carbon capture technology. This process is typically carried out continuously and uniformly. The performance of the membrane in gas separation is influenced by crucial factors such as its material, configuration, design, and operational limitations [35–38]. Numerous studies have investigated membrane separation for removing CO_2 from the exhaust gas streams of power plants. Utilizing membrane technology for CO_2 capture in post-combustion processes poses challenges due to the low pressure of flue gas streams. Inorganic membranes have demonstrated the ability to withstand high temperatures and exhibit good mechanical stability. However, their high cost hinders their widespread deployment.

However, membranes are more effective in processes such as multistage operations and steam regeneration, which are often considered to be hurdles in membrane separation. Several porous inorganic membranes have been previously examined for capturing CO_2 from flue gas and other emission steams. Despite offering mechanical stability and the capability to endure high temperatures, inorganic membranes are costly, limiting their extensive use. Inorganic membranes have not yet been used in large-scale processes and have still not been widely scaled up. The main barrier to the widespread use of inorganic membranes continues to be the high manufacturing costs, durability, and reliability [39–42].

On the other hand, easily fabricated polymer-based membranes structured in concentric-fiber units have emerged as excellent alternatives for industrial-scale applications of membrane separation. Additionally, in the case of polymer-based synthesized concentric-fiber membranes arranged in units, inorganic membranes cannot match the packaging efficiency provided by polymer-based membranes. However, polymer-based composites membranes exhibit lower separation performance compared with inorganic membranes.

The efficiency of CO_2 capture using available polymer-based membranes is affected by factors such as their low CO_2/N_2 selectivity, susceptibility to impurities, and molecular stability, particularly for operations requiring high-pressure conditions. To be economically viable for post-combustion CO_2 capture, polymer-based membranes must maintain relatively high permeability and a minimum selectivity ratio of 200 for CO_2 over N_2 [43]. High permeability reduces the investment cost of the membrane separation process by negating the need for a large membrane surface area to achieve adequate separation performance. Polymer-based membranes are used in natural gas sweetening processes. Membrane Technology & Research Inc. (MTR) achieved a 90% CO_2 capture rate from an 880 MW coal-fired power plant using a membrane-based experimental-scale process [38]. The high selectivity of facilitated transport membranes (FTM) has been demonstrated. However, these membranes face issues of long-term stability and can be negatively affected by small amounts of acidic gases in the flue gas stream.

In contrast to spirally configured membranes, concentric-fiber membranes offer more compact modules, high surface area-to-volume ratios, and the ideal configuration for high production rates among the various commercially available membrane types [39,44]. Advanced membrane development is made possible through composite concentric-fiber membranes, which are made of a highly porous polymer-based substructure [39]. This polymer-based substructure is often supported by a fine selective layer with a diameter of less than a micrometer [45]. Mixed matrix membranes (MMM) are formed from the dispersion of highly selective molecular-sieve particles. The scaling advantage of polymer-based membranes is integrated with the separation efficiency of molecular-sieve materials to serve as a promising contactor.

MMMs extend beyond the recognized compromise threshold of polymer-based membranes and address the prevailing challenges related to the cost and processing of inorganic membranes. However, they are currently conceptual and will not be used in industries soon. In addition, their current methods of fabrication are expensive and intricate. Therefore, future developments in membrane CO_2 capture should focus on composite membranes that can outperform the best commercially available membranes by utilizing both polymer-based and inorganic components [46–49]. A comprehensive understanding of the challenges in developing integrated systems for emerging CO_2 membrane separation technologies requires the enhancement of integrated systems through various configurations and the reinforcement of material systems and processing methodologies.

2.3. CO_2 Capture Technologies: Adsorption

Many industries use porous solid materials to capture carbon dioxide from their flue gas emissions, effectively removing it. Various absorbents, such as molecular sieves, activated carbon, and graphene, have been tested for this purpose. These absorbents can be categorized as high-temperature or low-temperature materials, with the former including calcium oxides and double salts, and the latter including carbonaceous materials [50–53].

Low-temperature materials are usually physisorbents, while high-temperature ones are considered to be chemisorbents. Among the current low-temperature adsorbents are anchored amines, which interact strongly with CO_2 as physisorbents [54]. The chemical properties of the absorbent play a crucial role in the efficacy and economics of the adsorption process. To be effective for industrial-scale separation in any gas separation process, absorbents must meet specific requirements. These requirements include high selectivity and working capacity, durability, and rapid kinetics [55,56].

Achieving maximum efficiency also depends on optimizing critical parameters such as the cycle's configuration, the cycling time, the operating conditions, and the number of beds [54]. Despite their exceptional capacity and selectivity towards CO_2, the extensive scale of production and water-stability of MOF materials pose a challenge to their widespread use in the industry.

The development of hybrid absorbents, such as MOF-functionalized amines, could potentially address the issues with traditional absorbents and provide a successful and cost-effective method of capture for post-combustion processes [57]. The technique of CO_2 capture using PSA has gained considerable attention due to its cost-effectiveness and low energy needs. These scaling issues could potentially be addressed by state-of-the-art approaches that present opportunities for effective heat management. This heat management technique encompasses monolithic structures with optimal thermal regulation or concentric-fiber adsorbents utilizing a cooling agent embedded in the bore [58]. To efficiently improve the process of reducing energy and include the cooling time in the operation of TSAs, design modifications incorporating indirect heating processes such as heat exchangers, heating coils, and heating jackets should be integrated into adsorption-based separation techniques. While it is feasible to conquer the challenges of the absorption process through adsorption-based separation, the necessary or recommended technologies are still in their developmental phase and are not cost-effective [59–63].

Additionally, their extensive operation has yet to be fully executed. It is crucial to align the evaluation of the efficacy and processing considerations of high-performing adsorbents in their design, development, and assessment. Moreover, the characteristics of the absorbent that will be utilized should be factored into the design and optimization of any cyclic process [56,62].

2.4. CO_2 Capture Technologies: Chemical Looping

There are two primary methods for naturally separating carbon dioxide and water from flue gas streams, known as chemical looping combustion (CLC) and chemical looping reforming (CLR) [63]. These processes are cost-effective for CO_2 capture due to their lower thermal energy requirements, and they have the added benefit of significantly reducing the formation of NO_x. By combining IGCC with chemical looping, syngas can be produced as a byproduct of CO_2 captured before combustion. The large-scale application of these technologies heavily depends on the availability of appropriate oxygen carriers, as they rely on metal oxides to transport oxygen between the fuel reactors and the air [64].

Transition metal oxides play a crucial role in the chemical looping process due to their physical and chemical properties, as well as their environmental and economic impacts. The most important characteristics to consider are their reactivity in the reduction and oxidation cycle of the process. Furthermore, the transition metal oxides must be fully combusted to achieve optimal combustion efficiency. The oxidation catalysts discussed above can only partially meet the specified requirements [63].

While high pressures may offer advantages for CCS (carbon capture and storage) applications, overcoming the challenge of achieving high overall efficiency through high-pressure operation is another obstacle in the chemical looping process. Energy analysis has shown that the efficiency penalty associated with the post-combustion process of capture by calcium looping can often be as low as 6–8% [65–67]. Including heat recovery beds to transfer heat between the CO_2 stream and the solid particles entering the calciner is a significant improvement, resulting in decreased energy penalties.

Although some pilot-scale studies are currently being conducted, most of the available chemical technologies used in the energy generation sector are still in the experimental or initial development stages [68–70]. It is expected that these technologies will not be fully deployed by 2030 [14]. Addressing the technical challenges resulting from development of the materials and optimization of the process is crucial to advance the use of the current innovative chemical looping technologies. Utilizing new chemical looping processes based on the principles of metallic oxides such as calcium and copper can lead to a reduction in the cost of equipment and a significant increase in the efficiency of capture. These metal oxides can integrate exothermic and endothermic chemical reactions within a single solid matrix.

2.5. CO_2 Capture Technologies: Direct Capture from the Air

The process of selectively removing carbon dioxide directly from the environment is known as direct air capture (DAC). Researchers are increasingly interested in this method because it has the potential to address the challenges associated with transporting significant amounts of carbon dioxide from localized emission sources to suitable locations for geological sequestration. Unlike traditional capture methods that target only larger point source emitters, DAC has the capacity to reduce atmospheric CO_2 levels, which may help decrease the rate of CO_2 accumulation [41,71,72]. DAC is closely related to adsorption-based CO_2 capture, as the CO_2 in the air is diluted to about 400 PPM. However, there are considerable technological barriers that need to be overcome.

Efficient materials with strong binding affinities and high CO_2/N_2 selectivity are essential for DAC processes due to the extremely low concentration of CO_2. Some of these materials include MOFs, alkali-based carbonates, and various aqueous oxides such as sodium and potassium oxide solutions [41]. Even though a material may be highly effective for capturing CO_2 from large point sources, it might not be as efficient for DAC processes. Recent thermodynamic studies have indicated that as the absorption enthalpy increases at low carbon dioxide concentrations, the TSA process becomes more energy-efficient than the PSA process for DAC applications. The estimated cost of implementing DAC technology is higher than that of capturing CO_2 from large point sources. Addressing the significant uncertainty in the design and cost analysis of the DAC process requires clarification of the underlying assumptions.

Additionally, cost-effective and resilient materials are necessary for widespread applications of air capture. It is crucial to minimize the costs associated with adopting and commercially implementing the DAC process in its initial stages. One way to enhance the viability of the DAC process is to reduce the energy requirements by utilizing distributed renewable energy sources such as thermal energy from solar systems.

2.6. CO_2 Capture Technologies: Hybrid Processes

Hybrid separation, which combines two or more subsystems for capture, provides an economical and durable method of capture. It is a viable method aimed at reducing the overall cost of separation while improving efficiency. Hybrid processes have been widely used in gas separation. These processes use dual or multiple separation systems in series or parallel configurations. Various studies have been conducted to assess the viability of different hybrid solutions for CO_2 capture. Examples include membrane–PSA and membrane distillation [73].

American Air Liquide has recently developed a promising hybrid system that uses a hybrid membrane–cryogenic distillation technology to capture CO_2 at sub-ambient temperatures of -50 °C to -20 °C [74]. This innovative process aims to improve the efficiency and selective capacity of the membrane module, while reducing the energy and investment costs associated with CO_2 capture. The success of hybrid membrane systems lies in high-pressure permeation of the membrane, which is used for pressurizing and absorbing high-pressure materials. This approach can also reduce the cost of using heavy-duty pumps [73,75–77].

Additionally, the hybrid pressure–temperature swing adsorption process (PTSA) is another efficient method for reducing the energy expenditure of CO_2 capture [78,79]. This system can operate at significantly moderate pressure and temperature conditions, thereby reducing the energy costs [74]. Implementing the PTSA setup significantly reduced the deep vacuum required in PSA to produce highly concentrated CO_2 under elevated temperature conditions. This setup leads to economical operating conditions, rapid cycles, and the durability of the adsorbents [79].

The goal of designing the PTSA systems is to achieve efficient processes of heat and mass transfer during the respective phases of desorption and adsorption. Considering the present state of innovative technologies, it is imperative to explore hybrid processes as innovative methods to enhance the economics and efficiency of CO_2 separation. However, commercializing these hybrid systems will require extensive research to address the factors of uncertainty and examine them from the perspective of viability, process design, and environmental and economic considerations.

2.7. Overall Comparison of CO_2 Capture Technologies: Advantages and Disadvantages

An extensive examination of different CO_2 capture technologies has been provided, covering absorption, membrane separation, adsorption, chemical looping, direct air capture, and hybrid processes. Table 1 provides a summary of the benefits and drawbacks of each technology.

Table 1. Advantages and disadvantages of various CO_2 capture technologies.

CO_2 Capture Technologies	Benefits	Drawbacks	Ref.
Absorption	• A well-established technology that is widely used in various industries • High selectivity for CO_2 capture • Versatile and mature solvent options	• Energy-intensive solvent regeneration • Moderate to high initial and operating costs • Solvent degradation and corrosion challenges	[18]
Membrane separation	• Continuous operation with steady-state processes • Lower operating costs in specific applications such as sweetening of natural gas • High selectivity based on the choice of material	• High initial setup costs, particularly for advanced materials and systems • Limited scalability due to the constraints of the membrane materials • Challenges of membrane fouling and degradation	[25]
Adsorption	• Efficient CO_2 extraction using various materials • High selectivity and working capacity • Versatile applications for both pre-combustion and post-combustion processes	• Dependence on the adsorbent materials' properties and their durability • Energy requirements of regeneration • Challenges in scaling up for large-scale industrial use	[41]
Chemical looping	• Economically suitable oxygen carriers are used • Reduced formation of nitrogen oxide (NO_2) during combustion • Suitable for both combustion (CLC) and reforming (CLR) applications	• Challenges in the development of materials for suitable oxygen carriers • Challenges in maintaining high overall efficiency under high-pressure operation • Still in the experimental or conceptual stages	[73]

Table 1. *Cont.*

CO$_2$ Capture Technologies	Benefits	Drawbacks	Ref.
Direct air capture (DAC)	• Direct removal of CO$_2$ from the atmosphere • Relatively low impact on land use • Potential for lowering atmospheric CO$_2$ levels if widely adopted	• Technological obstacles, including the selection of efficient sorbents • Higher costs compared with capturing CO$_2$ from large point sources • Challenges in achieving cost-competitive viability	[72]
Hybrid processes	• Enhanced efficiency through dual or multiple subsystems • Potential cost reductions through improved heat integration • Suitable for various applications	• Operational complexities and increased maintenance challenges • Some processes are still in the early development stages	[18]

The landscape of CO$_2$ technologies offers a range of advantages and disadvantages tailored to specific industrial needs. While significant progress has been made, most technologies are still in the development phase, awaiting widespread application. It is crucial to bridge the gap between the materials' properties and the processes' performance for successful implementation. Integrating the expertise of material scientists and engineers is essential to uncover the intricate correlation between the materials' properties and the parameters of hybrid processes. This interdisciplinary approach is fundamental for designing distinctive and comprehensive next-generation carbon capture technologies aligned with environmental and economic considerations. Continuous collaboration among these fields will be instrumental in unlocking the full potential of CO$_2$ capture, bringing us closer to sustainable and efficient solutions for mitigating climate change.

3. Evaluating the Challenges and Opportunities Encountered in Processes of Utilizing CO$_2$

The utilization of CO$_2$ has been increasingly viewed as a practical way to generate renewable energy and produce various valuable byproducts. However, it is crucial that processes of utilizing CO$_2$ are safe, environmentally friendly, and economically viable [80]. Some common pathways for the utilization of CO$_2$ include enhanced oil recovery (EOR) chemical conversion, mineralization, and desalination processes. Figure 2 illustrates the diverse applications of carbon dioxide. The US Department of Energy categorizes technologies of CO$_2$ utilization into three main branches: EOR, mineralization, and the production of cement-polycarbonate plastics.

Notably, CO$_2$ is a byproduct of the process of synthesizing ammonia and is also generated during the fermentation and synthesis of ethylene oxide in crude oil refineries [4]. While CO$_2$ is currently used in various processes such as preserving food, in the beverage industry, water treatment, petrochemical processes [5,8], and EOR, industries only utilize about 1% of the total global carbon dioxide emissions as raw material [81,82]. Therefore, capturing CO$_2$ to produce valuable fine chemicals and transportation fuels is crucial.

3.1. Utilization of CO$_2$ for Enhanced Oil Recovery

CO$_2$ can be used to enhance the recovery of hydrocarbons from reservoir formations. Depending on the type of formation and the reserves, it can be used in oil reservoirs for CO$_2$-enhanced oil recovery (CO$_2$-EOR), in gas formations for CO$_2$-enhanced gas recovery (CO$_2$-EGR), and in saline aquifers for CO$_2$-enhanced deep saline water/brine recovery (CO$_2$-EWR) [83]. This covers the various applications of CO$_2$ in the process of enhanced oil recovery across different geological formations. Using CO$_2$ in these recovery methods involves different operational and processing mechanisms. Many studies have explored

these aspects, offering valuable insights into the effectiveness and complexities of CO_2-enhanced recovery in different areas [84,85].
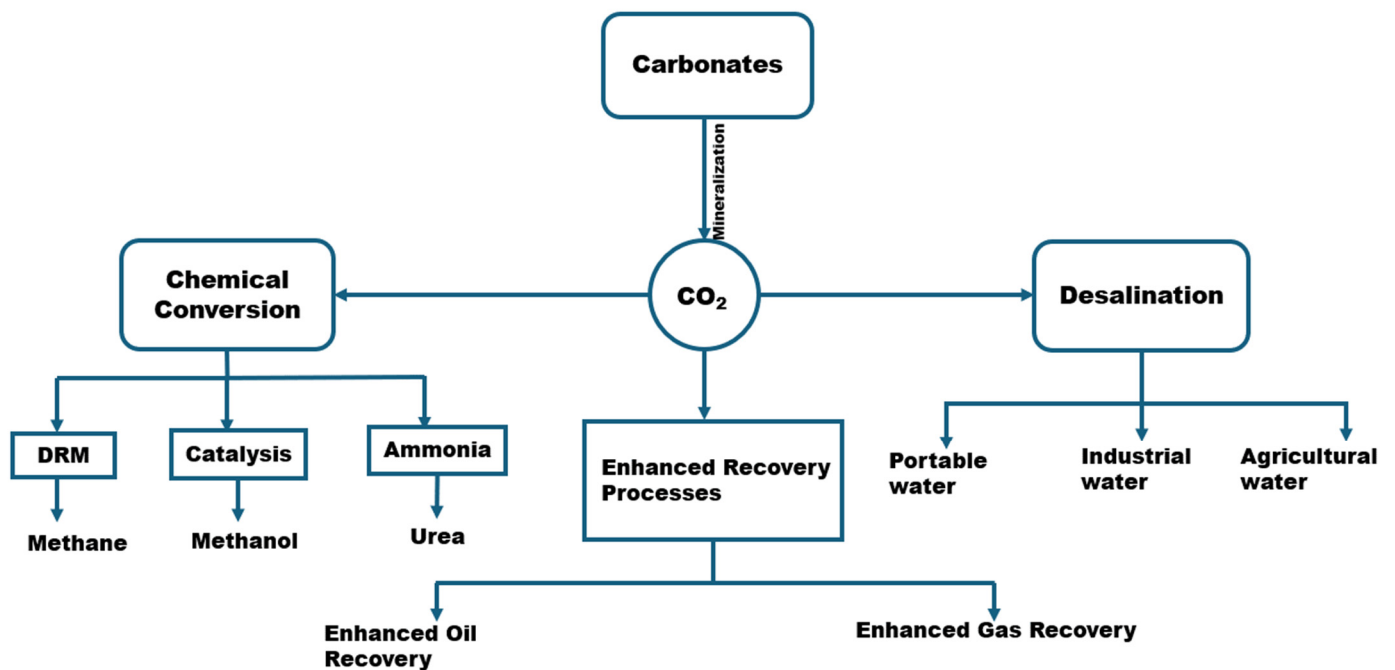

Figure 2. Different methods of utilizing CO_2.

3.1.1. CO_2-Enhanced Oil Recovery (CO_2-EOR)

Enhanced oil recovery involves the injection of substances into the reservoir to restore the formation's pressure and release any trapped hydrocarbons [86]. In CO_2-enhanced oil recovery (CO_2-EOR), crude oil is produced from the reservoir's formation by injecting CO_2. Once the mixture of CO_2 and crude oil is brought to the surface, the separated CO_2 is reinjected into the formation to start the cycle. Compared with other conventional oil recovery techniques, this process often produces more barrels of oil per reservoir [87,88]. CO_2 flooding is a widely accepted and effective technique for enhanced oil recovery (EOR). Its effectiveness is attributed to CO_2's role in enhancing the production of oil at the surface, achieved through its expansion and the reduction in the oil's density [83].

While naturally occurring CO_2 is used in most CO_2-EOR systems, recent studies have focused on using the carbon dioxide extracted from potentially harmful industrial gas streams [89]. There are two main techniques for conducting CO_2-EOR processes, namely water alternating with gas (WAG) and continuous gas injection (CGI) [90]. The former results in higher rates of recovering oil. An intermediate hydrocarbon, such as propane, can be added to CO_2-EOR to increase the efficiency of recovery by boosting the diffusion coefficient and displacement efficiency [91]. Figure 3 gives an illustration of the CO_2-enhanced oil recovery process.
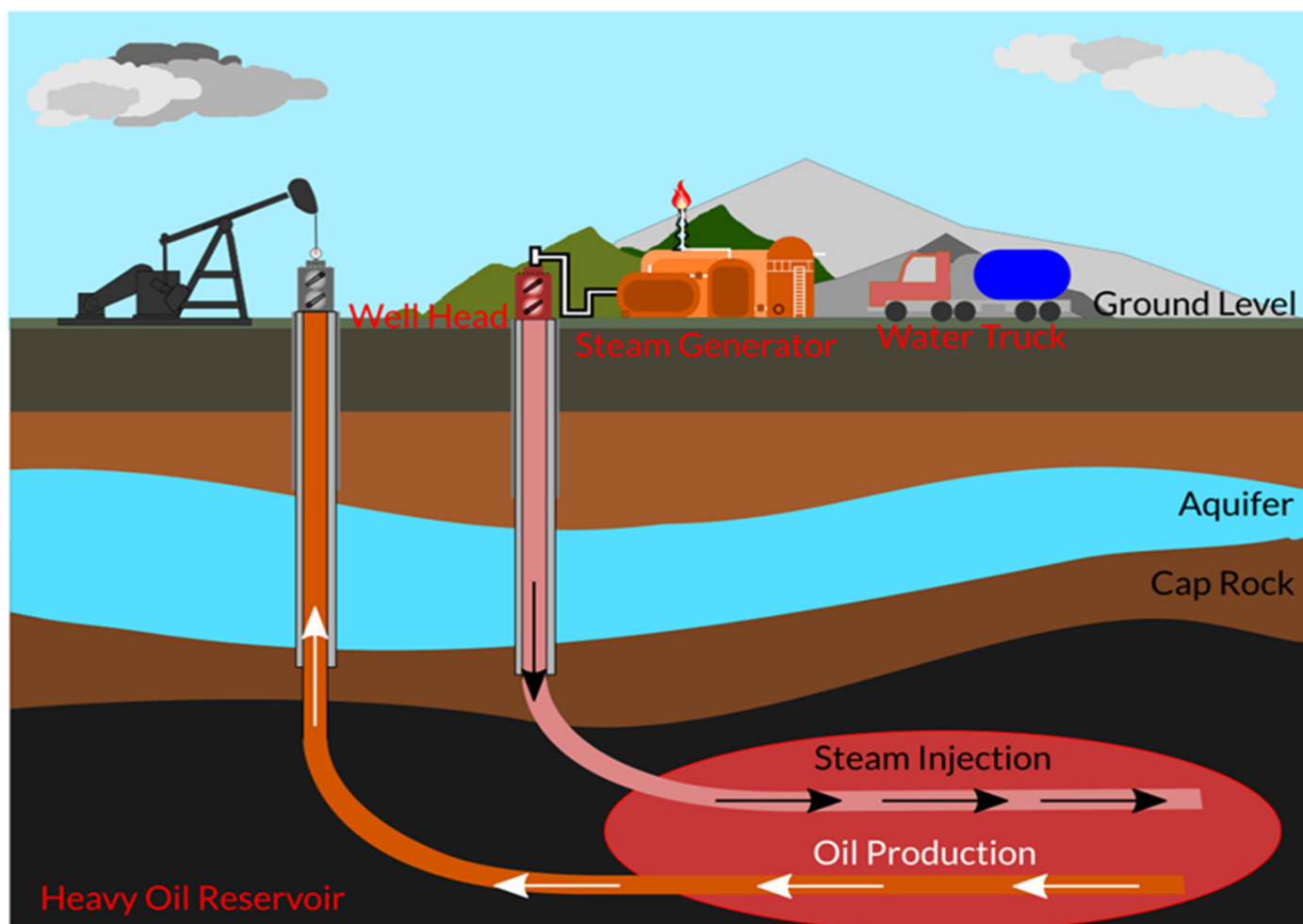
Figure 3. Illustration of the CO_2-enhanced oil/gas recovery process [92].

In general, the effectiveness of the CO_2-EOR process significantly depends on the temperature and pressure conditions within the reservoir's formation [93]. CO_2 EOR techniques often encounter several challenges. For instance, the fluid characteristics and capillary pressure of the reservoir's formation reduce the efficiency of the CO_2 flooding process because of the heterogeneity of the hydrocarbon formation between drilled wells [94]. Additionally, several factors are necessary for the successful execution of CO_2-EOR processes, such as production logs, rates of fluid production, and compensated neutron logs (CNL) [94]. Despite these limitations, numerous studies have focused on the efficiency of CO_2-EOR and -EGR processes, and these are expected to increase. Practically, the technology of CO_2-enhanced oil and gas recovery is a promising strategy that can be applied to most types of reservoirs. However, EOR processes only account for around 3% of global utilization of CO_2. Although the price of CO_2 has significantly hindered its advancements in EOR applications, the number of hydrocarbon formations utilizing CO_2 for enhanced oil recovery is steadily increasing [95–97].

3.1.2. CO_2-Enhanced Gas Recovery (CO_2-EGR)

The CO_2-enhanced gas recovery technique, also known as CO_2-EGR, is used in the oil and gas industry to boost the production of natural gas from mature reservoirs. This method involves injecting carbon dioxide (CO_2) into depleted oil and gas fields, leveraging the unique properties of CO_2 to stimulate increased gas production [84]. When CO_2 interacts with the reservoir's fluids and rock formations, it serves multiple purposes. It acts as a displacement agent, improving the sweep efficiency by reducing the reservoir's residual oil

and gas saturation [98]. Additionally, the injected CO_2 alters the properties of the reservoir's fluids, decreasing the oil's viscosity and enhancing the mobility of hydrocarbons, thereby extending the productive life of mature fields and making more efficient use of existing hydrocarbon resources [99].

Besides its role in enhanced gas recovery, CO_2-EGR plays a crucial part in carbon capture and storage processes. The injected CO_2 is sequestered underground, preventing its release into the atmosphere and curbing greenhouse gas emissions. This dual benefit of enhancing gas recovery while simultaneously addressing environmental concerns aligns CO_2-EGR with the broader objectives of sustainable energy practices [99]. Ongoing research in this field revolves around optimizing the injection strategies, understanding interactions with the reservoir, and developing technologies that maximize the recovery of hydrocarbon and minimize the environmental impacts [93,100]. As the energy industry shifts towards cleaner practices, CO_2-EGR stands as a promising approach that combines enhanced hydrocarbon production with environmental sustainability.

3.1.3. CO_2-Enhanced Water/Brine Recovery (CO_2-EWR)

The process of CO_2-enhanced water or brine recovery, referred to as CO_2-EWR, is a technique used in managing subsurface resources, especially in geothermal energy and unconventional production of oil and gas. Unlike traditional enhanced oil recovery (EOR) methods that mainly focus on the production of hydrocarbon, CO_2-EWR involves injecting carbon dioxide (CO_2) into underground formations to improve the recovery of water or brine resources [84,87]. This technique is particularly relevant in geothermal reservoirs, where CO_2 injections can enhance the circulation of fluid, increase permeability, and improve the efficiency of heat transfer [101]. In unconventional production of oil and gas, CO_2-EWR can be utilized to optimize the recovery of water, ensuring more sustainable and efficient use of water resources in hydraulic fracturing operations [102].

The process of CO_2-EWR relies on the unique properties of carbon dioxide to influence the physical and chemical properties of the subsurface fluids. The injected CO_2 can alter the viscosity of water or brine, promoting enhanced fluid flow and subsequently improving the overall recovery rates [103]. Moreover, this method contributes to carbon capture and storage (CCS) by sequestering CO_2 underground, addressing environmental concerns associated with greenhouse gas emissions. As researchers explore the potential applications and optimization of CO_2-EWR, it represents a promising approach to achieving more sustainable practices in the recovery of subsurface resources [22,104]. Ongoing studies are focused on understanding the complex interactions of CO_2, water or brine, and the reservoir's rock to enhance the efficiency and effectiveness of the CO_2 injection process [105]. There is also interest in developing new technologies and methodologies for improving the monitoring and management of CO_2 storage to ensure long-term stability and safety.

Additionally, CO_2 injection has significant implications for the geothermal industry. The injection of CO_2 can improve the extraction of geothermal fluids by enhancing the heat transfer capabilities of the reservoir. This is particularly beneficial in low-permeability geothermal reservoirs where circulation of the fluid is challenging. The improved fluid dynamics facilitated by CO_2 can lead to more efficient geothermal energy production, providing a renewable energy source with a lower carbon footprint. In unconventional production of oil and gas, CO_2 injection offers a means to manage water resources more sustainably. Figure 4 presents an illustration of the reservoir and surface components involved in the process of CO_2-enhanced water/brine recovery.
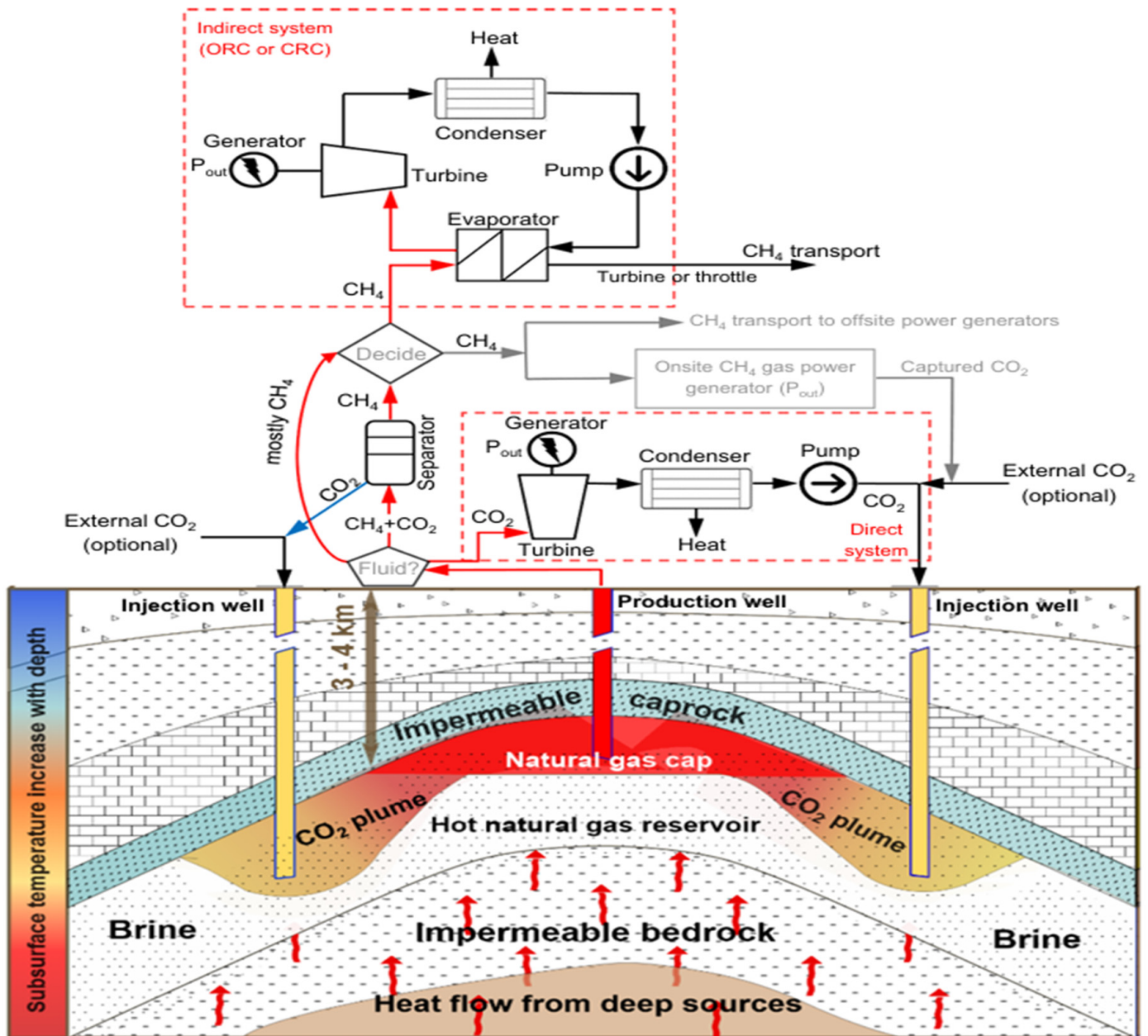
Figure 4. Illustration of the reservoir and surface components involved in the process of CO_2-enhanced water/brine recovery [105].

Hydraulic fracturing, or fracking, requires significant amounts of water, and the ability to recover and reuse water through CO_2 injection can reduce the environmental impact of fracking operations. This not only conserves water but also minimizes the disposal of wastewater, which is a major environmental concern in the industry. CO_2-enhanced water recovery represents a multifaceted approach that integrates the management of subsurface resources with environmental sustainability. By leveraging the properties of CO_2, this technique enhances the recovery of fluid while also providing a viable solution for carbon sequestration [22,104].

3.2. CO₂ Utilization: Conversion of CO₂ into Fuels and Petrochemicals

The utilization of CO_2 is expected to address several challenges associated with the large-scale implementation of CCS, including the high financial costs, commercial viability, and longevity. It also improves the process of CO_2 capture and offers the potential to

partially substitute for fossil fuels as the primary energy source [20]. Furthermore, it could pave way for the development of sustainable technologies that complement the existing fossil fuel resources.

3.2.1. CO_2 Utilization: Conversion of CO_2 into Fuels

The most effective method for utilizing CO_2 is by converting it into fuel. Captured CO_2 can be used as a raw material to produce various compounds such as methane, methanol, syngas, and alkanes, which are valuable in industries including fuel cells, power plants, and transportation [5]. Significant heat and an ample supply of catalysts are essential for substantial fuel production through the utilization of CO_2 due to its thermodynamic stability. The main processes for producing fuels from captured CO_2 are hydrogenation and dry reformation of methane (DRM) [106].

Hydrogenation of CO_2 is a promising approach, as it can recycle CO_2, store hydrogen, and address the challenge of electrical energy storage. [81]. The dry reformation of methane is considered to be one of the most efficient routes for the Fischer–Tropsch (FT) process, generating methanol as a byproduct and other significant liquid fuels [47,82,107,108]. A major challenge in CO_2 hydrogenation is the source of the hydrogen from fossil fuels, which could lead to increased CO_2 emissions [109–111].

To reduce the CO_2 emissions from hydrogenation, renewable energy sources such as solar, biomass, and wind can be considered as suitable substitutes for fossil fuels [4]. The low volumetric gas density of methane makes it unsuitable for the transportation industry [112]. Methane also has a relatively high global warming potential. It would be economically and environmentally inappropriate for the process of CO_2 capture to produce large amounts of methane, as it is already abundant in natural gas and other hydrocarbon gases. Therefore, producing methanol through CO_2 hydrogenation would be more beneficial [113,114].

Activating hydrocarbon bonds over existing copper-based catalysts to produce methanol is very challenging. The catalysts previously tested for this process have yet to yield good results. Although methanol has widespread use in petrochemical industries, combustion engines, and the production of organic solvents, the production of methanol makes only a marginal 0.1% difference to CO_2 emissions [113]. The reverse water–gas shift (RWGS) reaction is pivotal for the utilization of CO_2, transforming carbon dioxide into carbon monoxide, a crucial raw material in synthesizing methanol and hydrocarbon fuels through the Fischer–Tropsch (FT) reaction [114]. Two main challenges impeding the commercial-scale implementation and production of methanol are the endothermic nature of the RWGS reaction and the low conversion rates observed under moderate temperature conditions.

Another major challenge in commercial production of methanol is the production of active catalysts that can maximize production and enhance the reaction kinetics [115]. The comparison in Figure 5 shows that the continuous stirred-tank reactor (CSTR) outperforms the plug flow reactor (PFR) in terms of carbon conversion efficiency over time. Specifically, the CSTR maintains higher conversion rates than the PFR [116]. The figure also demonstrates that high local concentrations of methanol (MeOH) in the reactor lead to the formation of oxygen-containing carbonaceous species, resulting in rapid deactivation of the catalyst. On the other hand, low local concentrations of methanol lead to the formation of polycyclic aromatic hydrocarbons, causing slower deactivation of the catalyst [116]. This highlights the significance of controlling the concentration of methanol to optimize the catalyst's longevity and efficiency in processes of methanol production. The dry reformation of methane has recently directed researchers' focus to using CO_2 to produce syngas [117–119]. Syngas produced by the DRM process typically has a higher concentration than that generated from partial oxidation and steam reforming [120,121]. The DRM process produces only about 2% unreacted methane, significantly lower than steam reforming, making it suitable for generating liquid fuels at inaccessible natural gas sites [81].
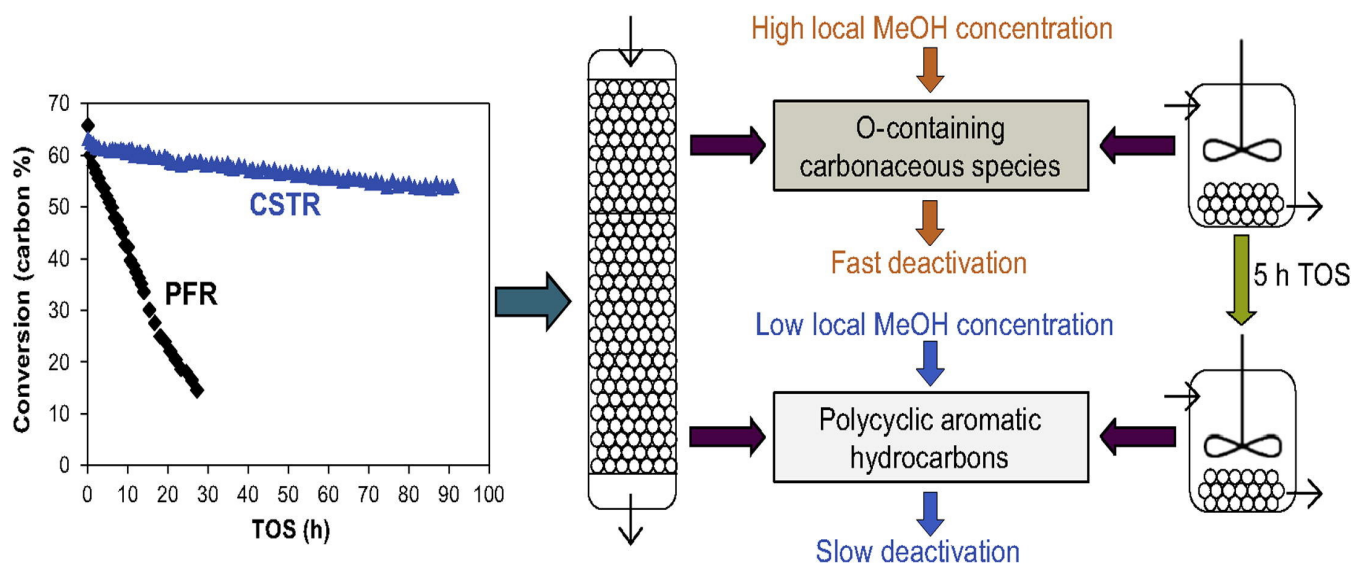
Figure 5. Pathways of the formation of coke and deactivation in the process of converting methanol [116].

Several research studies have been conducted on the viability of the DRM reaction using silica, alumina, and lanthanum oxide as supports for nickel, ruthenium, nickel-carbonyl, iridium, and rhodium [80]. Despite advancements in developing highly reactive catalysts with optimal stability for dry reformation of methane, finding a suitable catalyst for this reaction remains challenging due to the unavoidable process of deactivation through the formation of coke under high temperatures [121–124].

The oxidative hydrogenation of light alkanes to alkenes, utilizing carbon dioxide as a mild oxidant, represents a promising method with the potential to decrease the formation of coke, maintaining the stability of catalysts under high-temperature conditions [14,45,125–127]. By eliminating hydrogen through the RWGS reaction, carbon dioxide improves the equilibrium process of the aerobic dehydrogenation of lighter alkanes [128]. It is essential to regulate the temperature conditions because high heat could result in the overoxidation of the olefins, producing carbon oxides and significantly reducing selectivity [128]. Carbon dioxide is also used as an oxygen compound in the redox cycle process, directly influenced by the reducibility of the reactive metals and their supporting materials, as well as the mechanism of the reaction [129,130].

Therefore, the primary challenge in using captured CO_2 from industrial activities as a feedstock to produce synthetic fuel is the process of designing and developing innovative catalysts that demonstrate chemical durability, structural stability, high catalytic reactivity, and resistance to the formation of coke, among several other reaction conditions.

3.2.2. CO_2 Utilization: Conversion of CO_2 into Petrochemicals

Utilization of CO_2 involves converting carbon dioxide into a variety of valuable petrochemicals and fine chemicals [5,131]. One popular application is the use of CO_2 in producing urea, a widely used fertilizer. Additionally, CO_2 is used in the synthesis of polymers, medications, and other important petrochemicals such as urea resins and melamine [132].

Organic carbonates, such as DEC and CC, are also produced by capturing CO_2 and have various applications as pharmaceuticals, lubricants, catalytic reactions, and agrochemicals [80,82]. However, the process faces challenges, including the need for elevated temperatures and pressure conditions, as well as a large catalyst inventory. Separating the catalyst from the reaction products is also a significant challenge [80,82]. While AI-based catalysts are widely used, they are not considered environmentally friendly. An alternative environmentally friendly solution is the oxidative carboxylation process. Another impor-

tant substance obtained through the utilization of CO_2 is formic acid, which is produced through the hydrogenation of CO_2 and has various appealing factors, including the ability to store hydrogen in the liquid phase [81,133].

Additionally, biological utilization of carbon dioxide to produce biodiesel and other petrochemicals derived from biomass is another method [134]. Captured CO_2 needs purification before use as a feedstock in photobioreactors to eliminate contaminants that are harmful to the development of organisms [135]. CO_2 has various non-chemical applications such as in beverages, dry cleaning, food preservation, air conditioning, and solvents [5,80,81]. Even though there is a commercial market for converting captured CO_2 into fuels and petrochemicals, the researched materials must be economically and chemically stable. The conversion rates of CO_2 and the generation of its primary products need to meet the requirements of commercial use. Moreover, further research is needed to understand the reaction mechanisms influencing the chemical conversion of carbon dioxide. As of now, evaluation of the process and the operation's requirements are not fully understood.

3.3. Mineralization of CO_2

The process of CO_2 mineralization involves storing carbon dioxide using metallic oxides such as calcium and magnesium. The carbonation of calcium and magnesium silicates occurs naturally through a slow and thermodynamically favored reaction with atmospheric CO_2, also known as natural weathering [136]. Artificially enhancing the kinetics of carbonation can be achieved by increasing the temperature and injecting fluids with a higher concentration of carbon dioxide. Scaling up the process of mineralization faces a primary challenge in the slow kinetics of the reaction, despite significant efforts to speed it up [5].

Achieving over 80% carbonation efficiency requires high pressures of approximately 10–15 MPa and temperature conditions of 150–600 °C [5]. Additionally, the process involves extracting, processing, and transporting rock formations, and the carbonation reaction takes a long time, about 6–24 h, requiring rocks to be mined with diameters of about 37 mm. Furthermore, large plant sizes and the demanding requirements of additives result in high penalty costs [137].

Mineralization is a form of sequestration aimed at the permanent storage of CO_2. Unlike geological sequestration, which may experience leakages, carbonates are considered to be safe and stabilized [138]. The exothermic nature of the mineralization reaction, combined with the geothermal gradient of the formation, could lead to reduced energy consumption. Moreover, flue gas captured from industrial facilities can be directly utilized for mineralization processes without the need for purification [139]. Indirect CO_2 storage, known as indirect carbonation, can be used in industrial reactors to overcome technological and operational limitations, yielding high efficiency and purity of carbonation in reduced time and under mild conditions [140,141].

The process of mineralization also yields various products, such as silica, iron oxide, and carbonates of magnesium and calcium, which can help offset its expenses. However, the complexity of the process requires independent optimization of each operating condition [5]. High energy costs are a significant barrier to its commercialization. Alternate materials, such as sodium hydroxide, acetic acids, and ammonium salts, are used to reduce energy, while using more sophisticated materials to accelerate the reaction kinetics increases the process's efficiency [136,140–142]. Indirect mineral carbonation is considered to be the most beneficial method and is expected to see significant growth in size [87]. Recent advancements in in situ mineralization in basaltic rock using the indirect method of mineral carbonation highlight its potential for growth [143]. Future studies in this area should focus on upgrading the waste generated from alkali metals into highly commercial products through carbonation, for instance, through the precipitation of highly concentrated $CaCO_3$ [141,142].

3.4. Desalination and Water Production

The process of desalination and water production involves a promising approach to converting brine to water and removing the total dissolved solids (TDS) by utilizing captured CO_2 [144,145]. This water can be used in areas where potable water is scarce [133]. Currently, most industrial desalination plants do not use CO_2 due to financial limitations, but innovative technologies are being developed to make the utilization of CO_2 more affordable and effective. One method involves exposing ammonia-treated seawater to carbon dioxide, which creates weak bonds, separating the ions in the water phase [125].

The resulting products, NA_2CO_2 and NH_4CL, can sink to the bottom of the container due to their weight. The NH_4CL can be recycled using heat and calcium oxide, or by using it to produce ammonia and chlorine [39,146]. Another method of desalination is the formation of hydrate, which separates salts from water using carbon dioxide. The CO_2 hydrates formed can then be disposed of into the ocean or other water bodies [147]. Additionally, the forward osmosis process, which involves ammonia and carbon dioxide, represents another significant desalination method using CO_2 [148]. Reverse osmosis is another desalination method that relies on hydraulic pressure as its driving force, leveraging osmotic pressure to separate brine and fresh water through a "draw" solution.

A major challenge to this process is the large quantity of brine waste generated [149]. Furthermore, the local ecosystem can be negatively impacted by metal corrosion, solvent chemical residues, and high salt concentrations [150]. To address these challenges, carbonation, filtration, and recovery are the suggested primary units for use with chloride and amine compounds [151]. To address these challenges, carbonation, filtration, and recovery are the suggested primary units for use with chloride and amine compounds [152]. The economic implications of CO_2-based desalination processes indicate that the costs of producing treated water are higher than the alternative options. It is unlikely that the desalination process will become commercially viable without a substantial cost benefit. Despite CO_2 showing promise for desalination, the financial implications of producing potable water using CO_2-based technologies are currently higher than the alternative options, making the technology less likely to be applied in agricultural operations.

3.5. Challenges and Opportunities in the Utilization of CO_2

Technologies of carbon utilization show a lot of promise, offering numerous opportunities in various sectors. The focus has now shifted from simply storing CO_2 in saline waterbodies to considering captured CO_2 as a valuable and sustainable energy source.

3.5.1. Challenges

➢ Affordability: The widespread adoption of technologies of CO_2 utilization depends on their affordability. The economic feasibility of these innovations will be crucial in determining their acceptance and integration into existing industrial processes.
➢ Efficiency concerns: The current challenges evolve around the efficiency of technologies of CO_2 utilization. Researchers are actively working to tackle issues related to the high costs and low efficiency, aiming to improve the overall performance and competitiveness of these processes.
➢ Limited utilization: Despite CO_2 being captured from flue gas streams, its utilization in energy production and the synthesis of materials remains relatively low. The primary barriers to broader adoption are the expected high costs and the efficiency limitations of the existing technologies.

3.5.2. Opportunities

➢ Diverse applications: The potential for using CO_2 in various sectors is significant. This provides a versatile way to meet energy needs sustainably. Shifting this perspective opens new applications that go beyond traditional carbon capture and storage methods.
➢ Emerging technologies: Continual advancements in CO_2 utilization technologies, including the innovative processes mentioned earlier, indicate a transformative phase.

These new technologies hold the promise of producing petrochemicals and fuels from captured CO_2, representing a major shift in the use of greenhouse gases.

➢ Economic momentum: The economic aspects of utilizing CO_2 are becoming a focal point in research. The potential for economic benefits, such as the production of valuable materials, is generating interest and investment in these technologies.

In summary, the utilization of CO_2 presents promising opportunities despite the ongoing challenges. The shift from viewing CO_2 solely as a sequestered compound to recognizing its potential as a valuable energy resource signals a paradigm shift in sustainability practices. The development of these technologies will be influenced by effectively addressing the challenges and capitalizing on the emerging opportunities.

4. Evaluating the Synergy between the Processes of CO_2 Capture and Its Utilization

Combining the capture and utilization of CO_2 helps reduce the high energy costs of producing fuels and petrochemicals from flue gas streams, especially under the same temperature conditions. This integration holds the potential for cleaner and more energy-efficient technologies. Integrated processes of CO_2 capture and its utilization have been applied in the separation and reaction of gas. For instance, membrane reactors (MRs) combine chemical reactions with membrane separation, speeding up the reaction process and promoting equilibrium reactions on the product side. Similarly, sorption-enhanced reaction (SER) combines adsorption and reaction into a single unit [153–155].

The WGS process can operate at relatively high temperatures (about 350 °C), with favorable reaction kinetics due to the in-situ capture of CO_2 [156–162]. These innovative concepts can be applied across various industries to capture and utilize CO_2 simultaneously [158]. Previously, the commercial production of syngas (CO and H_2) has been achieved by directly converting industrial flue gases into chemicals and fuels using a dual-function material [161]. Syngas is essential for the synthesis of methanol. Another process, tri-reforming of methane, uses supported nickel catalysts to reform CO_2, steam-reform methane, and partially oxidize methane in a single reactor at around 850 °C [78,161,162]. Synthetic methane has been produced through in situ capture and methanation of CO_2 using a double-function material, typically a monolith [49,70]. Another example is the hydrogenation of carbon dioxide in Figure 6 [158], while a combined process of capture and reduction has been demonstrated at an experimental scale in the United States, involving the simultaneous capture and mineralization of carbon dioxide from the combustion of flue gas using coal [156,157].
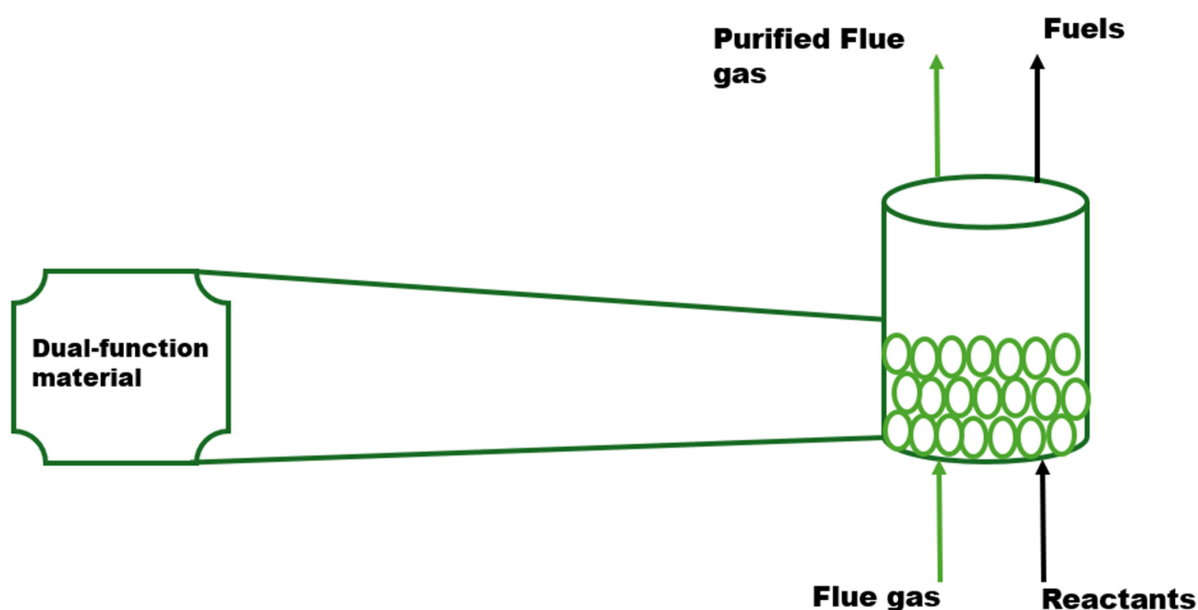

Figure 6. Schematic of the combined process of capture and utilization of carbon [158].

The resolution to the current global energy and environmental challenges may lie in integrated systems. Advancements in engineering processes and material science are crucial for developing new capture–conversion technologies. Achieving highly efficient and cost-effective technologies involves a thorough investigation of the composite adsorbents and catalysts, the operating conditions, and processing conditions, considering the distinct characteristics of adsorption and catalytic processes. Moreover, the materials' resilience to impurities, especially catalysts, may pose a challenge when utilizing waste gas streams directly. As a result, necessary measures need to be implemented to ensure the long-term efficiency of the material.

5. Conclusions

This review investigated the current obstacles and possible future prospects for carbon capture and utilization (CCU) technologies, with a focus on their efficiency and cost implications. Recent progress has resulted in significant advancements in designing and developing various CCU technologies, some of which are already in industrial use. However, most of the technologies under consideration are still in the experimental or laboratory stage. Integrating new materials that outperform the current state of the art for each technique could substantially decrease the energy requirements of both the capture and utilization processes.

Nonetheless, it is essential that the development of these new materials align closely with considerations of the processes' performance to accurately evaluate their potential under real-world conditions. A comprehensive approach that encourages collaboration between materials scientists and process engineers will greatly improve the scalability of CCU technologies. Moreover, small-scale assessments should consider the prerequisites of large-scale deployment to provide realistic evaluations of their performance and minimize uncertainties in estimations of the cost. Ultimately, cost-effectiveness remains a critical factor in determining the feasibility and widespread adoption of emerging CCU technologies.

Conflicts of Interest: The authors state that they do not have any known financial interests or personal relationships that could have influenced the work reported in this article.

References

1. Keerthana, K.B.; Wu, S.W.; Wu, M.E.; Kokulnathan, T. The United States Energy Consumption and Carbon Dioxide Emissions: A Comprehensive Forecast Using a Regression Model. *Sustainability* **2023**, *15*, 7932. [CrossRef]
2. Schwarz-Herion, O. The impact of the climate change discussion on society, science, culture, and politics: From the Limits to Growth via the Paris agreement to a binding global policy. In *The Impact of Climate Change on Our Life: The Questions of Sustainability*; Springer: Singapore, 2018; pp. 1–32. [CrossRef]
3. Markewitz, P.; Kuckshinrichs, W.; Leitner, W.; Linssen, J.; Zapp, P.; Bongartz, R.; Schreiber, A.; Muller, T.E. Worldwide innovations in the development of carbon capture technologies and the utilization of CO_2. *Energy Environ. Sci.* **2012**, *5*, 7281–7305. [CrossRef]
4. Boot-Handford, M.E.; Abanades, J.C.; Anthony, E.J.; Blunt, M.J.; Brandani, S.; Mac Dowell, N.; Fernandez, J.R.; Ferrari, M.-C.; Gross, R.; Hallett, J.P.; et al. Carbon capture and storage update. *Energy Environ. Sci.* **2013**, *7*, 130–189. [CrossRef]
5. Rubin, E.S.; Davison, J.E.; Herzog, H.J. The cost of CO_2 capture and storage. *Int. J. Greenh. Gas Control* **2015**, *40*, 378–400. [CrossRef]
6. Liotta, L.F.; Wu, H. CO_2 Capture, Utilization and Storage: Catalysts Design. *Catalysts* **2024**, *14*, 80. [CrossRef]
7. Karayil, A.; Elseragy, A.; Aliyu, A.M. An Assessment of CO_2 Capture Technologies towards Global Carbon Net Neutrality. *Energies* **2024**, *17*, 1460. [CrossRef]
8. Ahmed, S.; Irshad, M.; Yoon, W.; Karanwal, N.; Sugiarto, J.R.; Khan, M.K.; Kim, S.K.; Kim, J. Evaluation of MgO as a promoter for the hydrogenation of CO_2 to long-chain hydrocarbons over Fe-based catalysts. *Appl. Catal. B* **2023**, *338*, 123052. [CrossRef]
9. Khan, M.K.; Butolia, P.; Jo, H.; Irshad, M.; Han, D.; Nam, K.-W.; Kim, J. Selective Conversion of Carbon Dioxide into Liquid Hydrocarbons and Long-Chain α-Olefins over Fe-Amorphous AlO_x Bifunctional Catalysts. *ACS Catal.* **2020**, *10*, 10325–10338. [CrossRef]

10. Ahmed, S.; Bibi, S.S.; Irshad, M.; Asif, M.; Khan, M.K.; Kim, J. Synthesis of Long-chain Paraffins over Bimetallic Na–Fe$_{0.9}$Mg$_{0.1}$O$_x$ by Direct CO$_2$ Hydrogenation. *Top. Catal.* **2024**, *67*, 363–376. [CrossRef]

11. Ali, M.; Koo, H.M.; Kasipandi, S.; Han, G.Y.; Bae, J.W. Direct synthesis of liquid fuels and aromatics from syngas over mesoporous FeZrOx catalyst mixed with Mo/ferrierite. *Fuel* **2020**, *264*, 116851. [CrossRef]

12. Kondratenko, E.V.; Mul, G.; Baltrusaitis, J.; Larrazábal, G.O.; Pérez-Ramírez, J. Status and perspectives of CO$_2$ conversion into fuels and chemicals by catalytic, photocatalytic and electrocatalytic processes. *Energy Environ. Sci.* **2013**, *6*, 3112–3135. [CrossRef]

13. Zafar, F.; Zhao, R.; Ali, M.; Min Park, Y.; Roh, H.S.; Gao, X.; Tian, J.; Bae, J.W. Unprecedented contributions of In2O3 promoter on ordered mesoporous Cu/Al2O3 for CO$_2$ hydrogenation to oxygenates. *Chem. Eng. J.* **2022**, *439*, 135649. [CrossRef]

14. Qiu, H.H.; Liu, L.G. A Study on the Evolution of Carbon Capture and Storage Technology Based on Knowledge Mapping. *Energies* **2018**, *11*, 1103. [CrossRef]

15. Kamkeng, A.D.N.; Wang, M.; Hu, J.; Du, W.; Qian, F. Transformation technologies for CO$_2$ utilisation: Current status, challenges and future prospects. *Chem. Eng. J.* **2021**, *409*, 128138. [CrossRef]

16. Eyitayo, S.I.; Okere, C.J.; Hussain, A.; Gamadi, T.; Watson, M.C. Synergistic sustainability: Future potential of integrating produced water and CO$_2$ for enhanced carbon capture, utilization, and storage (CCUS). *J. Environ. Manag.* **2024**, *351*, 119713. [CrossRef]

17. Miller, D.C.; Litynski, J.T.; Brickett, L.A.; Morreale, B.D. Toward transformational carbon capture systems. *AIChE J.* **2016**, *62*, 2–10. [CrossRef]

18. Zhao, Y.; Ho, W.S.W. CO$_2$-selective membranes containing sterically hindered amines for CO$_2$/H$_2$ separation. *Ind. Eng. Chem. Res.* **2013**, *52*, 8774–8782. [CrossRef]

19. Songolzadeh, M.; Soleimani, M.; Takht Ravanchi, M.; Songolzadeh, R. Carbon dioxide separation from flue gases: A technological review emphasizing reduction in greenhouse gas emissions. *Sci. World J.* **2014**, *2014*, 828131. [CrossRef]

20. Abotalib, M.; Zhao, F.; Clarens, A. Deployment of a Geographical Information System Life Cycle Assessment Integrated Framework for Exploring the Opportunities and Challenges of Enhanced Oil Recovery Using Industrial CO$_2$ Supply in the United States. *ACS Sustain. Chem. Eng.* **2016**, *4*, 4743–4751. [CrossRef]

21. Ahn, Y.; Bae, S.J.; Kim, M.; Cho, S.K.; Baik, S.; Lee, J.I.; Cha, J.E. Review of supercritical CO$_2$ power cycle technology and current status of research and development. *Nucl. Eng. Technol.* **2015**, *47*, 647–661. [CrossRef]

22. Ali, M.; Jha, N.K.; Pal, N.; Keshavarz, A.; Hoteit, H.; Sarmadivaleh, M. Recent advances in carbon dioxide geological storage, experimental procedures, influencing parameters, and future outlook. *Earth Sci. Rev.* **2022**, *225*, 103895. [CrossRef]

23. Boundary Dam Integrated Carbon Capture and Storage Demonstration Project. 2015. Available online: http://www.saskpower. com/our-power-future/carbon-capture-and-storage/ (accessed on 25 November 2016).

24. Arstad, B.; Fjellvåg, H.; Kongshaug, K.O.; Swang, O.; Blom, R. Amine functionalised metal organic frameworks (MOFs) as adsorbents for carbon dioxide. *Adsorption* **2008**, *14*, 755–762. [CrossRef]

25. Builes, S.; López-Aranguren, P.; Fraile, J.; Vega, L.F.; Domingo, C. Analysis of CO$_2$ adsorption in amine-functionalized porous silicas by molecular simulations. *Energy Fuels* **2015**, *29*, 3855–3862. [CrossRef]

26. Kong, Y.; Shen, X.; Fan, M.; Yang, M.; Cui, S. Dynamic capture of low-concentration CO$_2$ on amine hybrid silsesquioxane aerogel. *Chem. Eng. J.* **2016**, *283*, 1059–1068. [CrossRef]

27. Goeppert, A.; Czaun, M.; Surya Prakash, G.K.; Olah, G.A. Air as the renewable carbon source of the future: An overview of CO$_2$ capture from the atmosphere. *Energy Environ. Sci.* **2012**, *5*, 7833–7853. [CrossRef]

28. Bates, E.D.; Mayton, R.D.; Ntai, I.; Davis, J.H. CO$_2$ capture by a task-specific ionic liquid. *J. Am. Chem. Soc.* **2002**, *124*, 926–927. [CrossRef]

29. Cadena, C.; Anthony, J.L.; Shah, J.K.; Morrow, T.I.; Brennecke, J.F.; Maginn, E.J. Why is CO$_2$ so Soluble in Imidazolium-Based Ionic Liquids? *J. Am. Chem. Soc.* **2004**, *126*, 5300–5308. [CrossRef]

30. Corvo, M.C.; Sardinha, J.; Casimiro, T.; Marin, G.; Seferin, M.; Einloft, S.; Menezes, S.C.; Dupont, J.; Cabrita, E.J. A Rational Approach to CO$_2$ Capture by Imidazolium Ionic Liquids: Tuning CO$_2$ Solubility by Cation Alkyl Branching. *ChemSusChem* **2015**, *8*, 1935–1946. [CrossRef] [PubMed]

31. Rochelle, G.T. Amine Scrubbing for CO$_2$ Capture. *Science (1979)* **2009**, *325*, 1652–1654. [CrossRef]

32. Lively, R.P.; Realff, M.J. On thermodynamic separation efficiency: Adsorption processes. *AIChE J.* **2016**, *62*, 3699–3705. [CrossRef]

33. Soo, X.Y.D.; Lee, J.J.C.; Wu, W.Y.; Tao, L.; Wang, C.; Zhu, Q.; Bu, J. Advancements in CO$_2$ capture by absorption and adsorption: A comprehensive review. *J. CO2 Util.* **2024**, *81*, 102727. [CrossRef]

34. Godin, J.; Liu, W.; Ren, S.; Xu, C.C. Advances in recovery and utilization of carbon dioxide: A brief review. *J. Environ. Chem. Eng.* **2021**, *9*, 105644. [CrossRef]

35. Han, S.; Huang, Y.; Watanabe, T.; Dai, Y.; Walton, K.S.; Nair, S.; Scholl, D.S.; Carson, M.J. High-throughput screening of metal-organic frameworks for CO$_2$ separation. *ACS Comb. Sci.* **2012**, *14*, 263–267. [CrossRef] [PubMed]

36. Huang, Q.; Eić, M. Commercial adsorbents as benchmark materials for separation of carbon dioxide and nitrogen by vacuum swing adsorption process. *Sep. Purif. Technol.* **2013**, *103*, 203–215. [CrossRef]

37. Japip, S.; Wang, H.; Xiao, Y.; Chung, T.S. Highly permeable zeolitic imidazolate framework (ZIF)-71 nano-particles enhanced polyimide membranes for gas separation. *J. Memb. Sci.* **2014**, *467*, 162–174. [CrossRef]

38. Merkel, T.C.; Lin, H.; Wei, X.; Baker, R. Power plant post-combustion carbon dioxide capture: An opportunity for membranes. *J. Memb. Sci.* **2010**, *359*, 126–139. [CrossRef]

39. Koros, W.J. Evolving Beyond the Thermal Age of Separation Processes: Membranes Can Lead the Way. *AIChE J.* **2004**, *50*, 2326–2334. [CrossRef]

40. Kosuri, M.R.; Koros, W.J. Asymmetric hollow fiber membranes for separation of CO_2 from hydrocarbons and fluorocarbons at high-pressure conditions relevant to C 2F4 polymerization. *Ind. Eng. Chem. Res.* **2009**, *48*, 10577–10583. [CrossRef]

41. Rownaghi, A.A.; Kant, A.; Li, X.; Thakkar, H.; Hajari, A.; He, Y.; Brennan, P.J.; Hosseini, H.; Koros, W.J.; Rezaei, F. Aminosilane-Grafted Zirconia–Titiania–Silica Nanoparticles/Torlon Hollow Fiber Composites for CO_2 Capture. *ChemSusChem* **2016**, *9*, 1166–1177. [CrossRef]

42. Favre, E. Carbon dioxide recovery from post-combustion processes: Can gas permeation membranes compete with absorption? *J. Memb. Sci.* **2007**, *294*, 50–59. [CrossRef]

43. Kim, T.J.; Vrålstad, H.; Sandru, M.; Hägg, M.B. Separation performance of PVAm composite membrane for CO_2 capture at various pH levels. *J. Memb. Sci.* **2013**, *428*, 218–224. [CrossRef]

44. Cheng, Y.; Zhang, F.; Zhang, Y.; Miao, C.; Hua, W.; Yue, Y.; Gao, Z. Oxidative dehydrogenation of ethane with CO_2 over Cr supported on submicron ZSM-5 zeolite. *Chin. J. Catal.* **2015**, *36*, 1242–1248. [CrossRef]

45. Bae, T.H.; Long, J.R. CO_2/N_2 separations with mixed-matrix membranes containing Mg_2(dobdc) nanocrystals. *Energy Environ. Sci.* **2013**, *6*, 3565–3569. [CrossRef]

46. Fan, M.; Abdullah, A.Z.; Bhatia, S. Catalytic Technology for Carbon Dioxide Reforming of Methane to Synthesis Gas. *ChemCatChem* **2009**, *1*, 192–208. [CrossRef]

47. Tanh Jeazet, H.B.; Staudt, C.; Janiak, C. Metal–organic frameworks in mixed- matrix membranes for gas separation. *Dalton Trans.* **2012**, *41*, 14003–14027. [CrossRef] [PubMed]

48. Labreche, Y.; Lively, R.P.; Rezaei, F.; Chen, G.; Jones, C.W.; Koros, W.J. Post-spinning infusion of poly(ethyleneimine) into polymer/silica hollow fiber sorbents for carbon dioxide capture. *Chem. Eng. J.* **2013**, *221*, 166–175. [CrossRef]

49. Chue, K.T.; Kim, J.N.; Yoo, Y.J.; Cho, S.H.; Yang, R.T. Comparison of Activated Carbon and Zeolite 13X for CO_2 Recovery from Flue Gas by Pressure Swing Adsorption. *Ind. Eng. Chem. Res.* **1995**, *34*, 591–598. [CrossRef]

50. Liu, H.; Guo, P.; Regueira, T.; Wang, Z.; Du, J.; Chen, G. Irreversible Change of the Pore Structure of ZIF-8 in Carbon Dioxide Capture with Water Coexistence. *J. Phys. Chem. C* **2016**, *120*, 13287–13294. [CrossRef]

51. Patel, H.A.; Karadas, F.; Canlier, A.; Park, J.; Deniz, E.; Jung, Y.; Atilhan, M.; Yavuz, C.T. High capacity carbon dioxide adsorption by inexpensive covalent organic polymers. *J. Mater. Chem.* **2012**, *22*, 8431–8437. [CrossRef]

52. Phan, A.; Doonan, C.J.; Uribe-Romo, F.J.; Knobler, C.B.; Okeeffe, M.; Yaghi, O.M. Synthesis, structure, and carbon dioxide capture properties of zeolitic imidazolate frameworks. *Acc. Chem. Res.* **2010**, *43*, 58–67. [CrossRef]

53. Reich, T.E.; Behera, S.; Jackson, K.T.; Jena, P.; El-Kaderi, H.M. Highly selective $CO_2/CH4$ gas uptake by a halogen-decorated borazine-linked polymer. *J. Mater. Chem.* **2012**, *22*, 13524–13528. [CrossRef]

54. Choi, S.; Drese, J.H.; Jones, C.W. Adsorbent Materials for Carbon Dioxide Capture from Large Anthropogenic Point Sources. *ChemSusChem* **2009**, *2*, 796–854. [CrossRef]

55. Hauchhum, L.; Mahanta, P. Carbon dioxide adsorption on zeolites and activated carbon by pressure swing adsorption in a fixed bed. *Int. J. Energy Environ. Eng.* **2014**, *5*, 349–356. [CrossRef]

56. Ruthven, D.M. Principles of Adsorption and Adsorption Processes. Available online: https://books.google.com/books?hl=en&lr=&id=u7wq21njR3UC&oi=fnd&pg=PR17&dq=Principles+of+adsorption+and+adsorption+processes.&ots=wdStQpDetX&sig=bKK6mVjzEQ5ZmJQYCcW7I9OEr5I#v=onepage&q=Principles%20of%20adsorption%20and%20adsorption%20processes.&f=false (accessed on 29 January 2024).

57. Gao, X.-J.; Zheng, G. The difference in the CO_2 adsorption capacities of different functionalized pillar-layered metal–organic frameworks (MOFs). *Dalton Trans.* **2021**, *50*, 9310–9316. [CrossRef] [PubMed]

58. Rezaei, F.; Webley, P. Structured adsorbents in gas separation processes. *Sep. Purif. Technol.* **2010**, *70*, 243–256. [CrossRef]

59. Lively, R.P.; Chance, R.R.; Kelley, B.T.; Deckman, H.W.; Drese, J.H.; Jones, C.W.; Koros, W.J. Hollow fiber adsorbents for CO_2 removal from flue gas. *Ind. Eng. Chem. Res.* **2009**, *48*, 7314–7324. [CrossRef]

60. Lively, R.P.; Chance, R.R.; Koros, W.J. Enabling low-cost CO_2 capture via heat integration. *Ind. Eng. Chem. Res.* **2010**, *49*, 7550–7562. [CrossRef]

61. Rezaei, F.; Lively, R.P.; Labreche, Y.; Chen, G.; Fan, Y.; Koros, W.J.; Jones, C.W. Aminosilane-grafted polymer/silica hollow fiber adsorbents for CO_2 capture from flue gas. *ACS Appl. Mater. Interfaces* **2013**, *5*, 3921–3931. [CrossRef] [PubMed]

62. Kärger, J.; Ruthven, D.M. Self-diffusion and diffusive transport in zeolite crystals. *Stud. Surf. Sci. Catal.* **1997**, *105*, 1843–1850. [CrossRef]

63. Hossain, M.M.; de Lasa, H.I. Chemical-looping combustion (CLC) for inherent CO_2 separations—A review. *Chem. Eng. Sci.* **2008**, *63*, 4433–4451. [CrossRef]

64. Zhao, Z.; Zhang, H.; Jiao, C.; Wang, Q.; Lin, X. Review on Global CCUS Technology and Application. *Mod. Chem. Ind.* **2021**, *41*, 5–10. [CrossRef]

65. Martínez, A.; Lara, Y.; Lisbona, P.; Romeo, L.M. Energy penalty reduction in the calcium looping cycle. *Int. J. Greenh. Gas Control* **2012**, *7*, 74–81. [CrossRef]

66. Martínez, I.; Murillo, R.; Grasa, G.; Carlos Abanades, J. Integration of a Ca looping system for CO_2 capture in existing power plants. *AIChE J.* **2011**, *57*, 2599–2607. [CrossRef]

67. Romeo, L.M.; Usón, S.; Valero, A.; Escosa, J.M. Exergy analysis as a tool for the integration of very complex energy systems: The case of carbonation/calcination CO_2 systems in existing coal power plants. *Int. J. Greenh. Gas Control* **2010**, *4*, 647–654. [CrossRef]

68. Charitos, A.; Hawthorne, C.; Bidwe, A.R.; Sivalingam, S.; Schuster, A.; Spliethoff, H.; Scheffknecht, G. Parametric investigation of the calcium looping process for CO_2 capture in a 10 kWth dual fluidized bed. *Int. J. Greenh. Gas Control* **2010**, *4*, 776–784. [CrossRef]

69. Rodríguez, N.; Alonso, M.; Abanades, J.C. Experimental investigation of a circulating fluidized-bed reactor to capture CO_2 with CaO. *AIChE J.* **2011**, *57*, 1356–1366. [CrossRef]

70. Symonds, R.T.; Lu, D.Y.; Manovic, V.; Anthony, E.J. Pilot-scale study of CO_2 capture by CaO-based sorbents in the presence of steam and SO_2. *Ind. Eng. Chem. Res.* **2012**, *51*, 7177–7184. [CrossRef]

71. Lackner, K.S.; Brennan, S.; Matter, J.M.; Park, A.-H.A.; Wright, A.; van der Zwaan, B. The urgency of the development of CO_2 capture from ambient air. *Proc. Natl. Acad. Sci. USA* **2012**, *109*, 13156–13162. [CrossRef]

72. Sanz-Pérez, E.S.; Murdock, C.R.; Didas, S.A.; Jones, C.W. Direct Capture of CO_2 from Ambient Air. *Chem. Rev.* **2016**, *116*, 11840–11876. [CrossRef]

73. Zhao, L.; Primabudi, E.; Stolten, D. Investigation of a Hybrid System for Post-Combustion Capture. *Energy Procedia* **2014**, *63*, 1756–1772. [CrossRef]

74. Hasse, D.; Ma, J.; Kulkarni, S.; Terrien, P.; Tranier, J.P.; Sanders, E.; Chaubey, T.; Brumback, J. CO_2 Capture by Cold Membrane Operation. *Energy Procedia* **2014**, *63*, 186–193. [CrossRef]

75. Belaissaoui, B.; Le Moullec, Y.; Willson, D.; Favre, E. Hybrid membrane cryogenic process for post-combustion CO_2 capture. *J. Memb. Sci.* **2012**, *415–416*, 424–434. [CrossRef]

76. Esteves, I.A.A.C.; Mota, J.P.B. Simulation of a new hybrid membrane/pressure swing adsorption process for gas separation. *Desalination* **2002**, *148*, 275–280. [CrossRef]

77. Scholz, M.; Frank, B.; Stockmeier, F.; Falß, S.; Wessling, M. Techno-economic analysis of hybrid processes for biogas upgrading. *Ind. Eng. Chem. Res.* **2013**, *52*, 16929–16938. [CrossRef]

78. Song, C. Global challenges and strategies for control, conversion and utilization of CO_2 for sustainable development involving energy, catalysis, adsorption and chemical processing. *Catal. Today* **2006**, *115*, 2–32. [CrossRef]

79. Wurzbacher, J.A.; Gebald, C.; Steinfeld, A. Separation of CO_2 from air by temperature-vacuum swing adsorption using diamine-functionalized silica gel. *Energy Environ. Sci.* **2011**, *4*, 3584–3592. [CrossRef]

80. Aresta, M. *Carbon Dioxide as Chemical Feedstock*; Wiley: Weinheim, Germany, 2010; 394p.

81. Aresta, M.; Dibenedetto, A. Utilisation of CO_2 as a chemical feedstock: Opportunities and challenges. *Dalton Trans.* **2007**, 2975–2992. [CrossRef]

82. Aresta, M.; Dibenedetto, A.; Angelini, A. Catalysis for the valorization of exhaust carbon: From CO_2 to chemicals, materials, and fuels. technological use of CO_2. *Chem. Rev.* **2014**, *114*, 1709–1742. [CrossRef]

83. Tunio, S.Q.; Tunio, A.H.; Ghirano, N.A.; Mohamed, Z.; Adawy, E. Comparison of Different Enhanced Oil Recovery Techniques for Better Oil Productivity. *Int. J. Appl. Sci. Technol.* **2011**, *1*, 143–153.

84. Edouard, M.N.; Okere, C.J.; Ejike, C.; Dong, P.; Suliman, M.A.M. Comparative numerical study on the co-optimization of CO_2 storage and utilization in EOR, EGR, and EWR: Implications for CCUS project development. *Appl. Energy* **2023**, *347*, 121448. [CrossRef]

85. Safi, R.; Agarwal, R.K.; Banerjee, S. Numerical simulation and optimization of CO_2 utilization for enhanced oil recovery from depleted reservoirs. *Chem. Eng. Sci.* **2016**, *144*, 30–38. [CrossRef]

86. Ighalo, J.O.; Nwabueze, Q.A. Production and Economic Analysis of Enhanced Oil Recovery (EOR) by Water Flooding: A Case Study of Reservoir OD-48 in The Niger Delta Article Open Access Production and Economic Analysis of Enhanced Oil Recovery (EOR) by Wate r Flooding: A Case Study of Reservoir OD-48 in The Niger Delta. *Pet. Coal* **2020**, *62*, 103–113.

87. Bao, W.; Li, H.; Zhang, Y. Experimental investigation of enhanced carbonation by solvent extraction for indirect CO_2 mineral sequestration. *Greenh. Gases: Sci. Technol.* **2014**, *4*, 785–799. [CrossRef]

88. Azzolina, N.A.; Nakles, D.V.; Gorecki, C.D.; Peck, W.D.; Ayash, S.C.; Melzer, L.S.; Chatterjee, S. CO_2 storage associated with CO_2 enhanced oil recovery: A statistical analysis of historical operations. *Int. J. Greenh. Gas Control* **2015**, *37*, 384–397. [CrossRef]

89. Perera, M.S.A.; Gamage, R.P.; Rathnaweera, T.D.; Ranathunga, A.S.; Koay, A.; Choi, X. A Review of CO_2-Enhanced Oil Recovery with a Simulated Sensitivity Analysis. *Energies* **2016**, *9*, 481. [CrossRef]

90. Gozalpour, F.; Ren, S.R.; Tohidi, B. CO_2 Eor and Storage in Oil Reservoir. *Oil Gas Sci. Technol.* **2005**, *60*, 537–546. [CrossRef]

91. Cho, J.; Kim, T.H.; Lee, K.S. Modeling of CO_2 EOR Process Combined with Intermediate Hydrocarbon Solvents for Higher Recovery Efficiency. In Proceedings of the Society of Petroleum Engineers—SPE EOR Conference at Oil and Gas West Asia, OGWA, Muscat, Oman, 21–23 March 2016. [CrossRef]

92. CO2 Trapping Mechanisms Assessment Using Numerical and Analytical Methods-ProQuest. Available online: https://www.proquest.com/docview/2479067252?pq-origsite=gscholar&fromopenview=true&sourcetype=Dissertations%20&%20Theses (accessed on 24 July 2024).

93. Celia, M.A.; Bachu, S.; Nordbotten, J.M.; Bandilla, K.W. Status of CO_2 storage in deep saline aquifers with emphasis on modeling approaches and practical simulations. *Water Resour. Res.* **2015**, *51*, 6846–6892. [CrossRef]

94. Panda, M.; Nottingham, D.; Lenig, D. Systematic Surveillance Techniques for a Large Miscible WAG Flood. *SPE Reserv. Eval. Eng.* **2011**, *14*, 299–309. [CrossRef]

95. Al Hajeri, S.; Negahban, S.; Al-Yafei, G.; Al Basry, A. Design and Implementation of the First CO_2-EOR Pilot in Abu Dhabi, UAE. In Proceedings of the SPE EOR Conference at Oil and Gas West Asia 2010, OGWA—EOR Challenges, Experiences and Opportunities in the Middle East, Muscat, Oman, 31 March–2 April 2010; pp. 587–595. [CrossRef]

96. Ampomah, W.; Balch, R.S.; Grigg, R.B.; Will, R.; Dai, Z.; White, M.D. Farnsworth Field CO_2-EOR Project: Performance Case History. In Proceedings of the SPE—DOE Improved Oil Recovery Symposium, Tulsa, OK, USA, 11–13 April 2016. [CrossRef]

97. Pizarro, J.O.D.S.A.; Branco, C.C.M. Challenges in Implementing an EOR Project in the Pre-Salt Province in Deep Offshore Brasil. In Proceedings of the Society of Petroleum Engineers—SPE EOR Conference at Oil and Gas West Asia 2012, OGWA—EOR: Building Towards Sustainable Growth, Muscat, Oman, 16–18 April 2012; Volume 2, pp. 954–966. [CrossRef]

98. Klimkowski, Ł.; Nagy, S.; Papiernik, B.; Orlic, B.; Kempka, T. Numerical Simulations of Enhanced Gas Recovery at the Załęcze Gas Field in Poland Confirm High CO_2 Storage Capacity and Mechanical Integrity. *Oil Gas Sci. Technol. Rev. D'ifp Energ. Nouv.* **2015**, *70*, 655–680. [CrossRef]

99. Ren, B.; Duncan, I.J. Reservoir simulation of carbon storage associated with CO_2 EOR in residual oil zones, San Andres formation of West Texas, Permian Basin, USA. *Energy* **2019**, *167*, 391–401. [CrossRef]

100. Allen, M.J.; Faulkner, D.R.; Worden, R.H.; Rice-Birchall, E.; Katirtsidis, N.; Utley, J.E.P. Geomechanical and petrographic assessment of a CO_2 storage site: Application to the Acorn CO_2 Storage Site, offshore United Kingdom. *Int. J. Greenh. Gas Control* **2020**, *94*, 102923. [CrossRef]

101. Iglauer, S. CO_2-Water-Rock Wettability: Variability, Influencing Factors, and Implications for CO_2 Geostorage. *Acc. Chem. Res.* **2017**, *50*, 1134–1142. [CrossRef] [PubMed]

102. Saira; Janna, F.; Le-Hussain, F. Effectiveness of modified CO_2 injection at improving oil recovery and CO_2 storage—Review and simulations. *Energy Rep.* **2020**, *6*, 1922–1941. [CrossRef]

103. Ajayi, T.; Gomes, J.S.; Bera, A. A review of CO_2 storage in geological formations emphasizing modeling, monitoring and capacity estimation approaches. *Pet. Sci.* **2019**, *16*, 1028–1063. [CrossRef]

104. Verma, Y.; Vishal, V.; Ranjith, P.G. Sensitivity Analysis of Geomechanical Constraints in CO_2 Storage to Screen Potential Sites in Deep Saline Aquifers. *Front. Clim.* **2021**, *3*, 720959. [CrossRef]

105. Ezekiel, J.; Ebigbo, A.; Adams, B.M.; Saar, M.O. Combining natural gas recovery and CO_2-based geothermal energy extraction for electric power generation. *Appl. Energy* **2020**, *269*, 115012. [CrossRef]

106. Driverless Vehicles: Opportunity for Further Greenhouse Gas Emission Reductions on JSTOR. Available online: https://www.jstor.org/stable/26353861 (accessed on 29 January 2024).

107. Okere, C.J.; Sheng, J.J. Review on clean hydrogen generation from petroleum reservoirs: Fundamentals, mechanisms, and field applications. *Int. J. Hydrog. Energy* **2023**, *48*, 38188–38222. [CrossRef]

108. Graciani, J.; Mudiyanselage, K.; Xu, F.; Baber, A.E.; Evans, J.; Senanayake, S.D.; Stacchiola, D.J.; Liu, P.; Hrbek, J.; Fernandez Sanz, J.; et al. Highly active copper-ceria and copper-ceria-titania catalysts for methanol synthesis from CO_2. *Science (1979)* **2014**, *345*, 546–550. [CrossRef]

109. Laurenczy, G.; Laurenczy, G. Hydrogen Storage and Delivery: The Carbon Dioxide—Formic Acid Couple. *Chimia* **2011**, *65*, 663. [CrossRef]

110. Matsubu, J.C.; Yang, V.N.; Christopher, P. Isolated metal active site concentration and stability control catalytic CO_2 reduction selectivity. *J. Am. Chem. Soc.* **2015**, *137*, 3076–3084. [CrossRef]

111. Hu, B.; Guild, C.; Suib, S.L. Thermal, electrochemical, and photochemical conversion of CO_2 to fuels and value-added products. *J. CO2 Util.* **2013**, *1*, 18–27. [CrossRef]

112. Bansode, A.; Urakawa, A. Towards full one-pass conversion of carbon dioxide to methanol and methanol-derived products. *J. Catal.* **2014**, *309*, 66–70. [CrossRef]

113. Porosoff, M.D.; Yan, B.; Chen, J.G. Catalytic reduction of CO_2 by H_2 for synthesis of CO, methanol and hydrocarbons: Challenges and opportunities. *Energy Environ. Sci.* **2016**, *9*, 62–73. [CrossRef]

114. Fan, S.; Wang, H.; Wang, S.; Dong, M.; Fan, W. Recent progress in the deactivation mechanism of zeolite catalysts in methanol to olefins. *Sci. China Chem.* **2024**, 1–10. [CrossRef]

115. Müller, S.; Liu, Y.; Vishnuvarthan, M.; Sun, X.; Van Veen, A.C.; Haller, G.L.; Sanchez-Sanchez, M.; Lercher, J.A. Coke formation and deactivation pathways on H-ZSM-5 in the conversion of methanol to olefins. *J. Catal.* **2015**, *325*, 48–59. [CrossRef]

116. Thermochemical Processing of Biomass: Conversion into Fuels, Chemicals and Power. Available online: https://books.google.com/books?hl=en&lr=&id=AsOKDwAAQBAJ&oi=fnd&pg=PR15&dq=Thermochemical+processing+of+biomass:+conversion+into+fuels,+chemicals+and+power&ots=bGv8DAbA47&sig=szpfm4vOLxIXnOrCzO7iIeMwJtA#v=onepage&q=Thermochemical%20processing%20of%20biomass:%20conversion%20into%20fuels,%20chemicals%20and%20power&f=false (accessed on 29 January 2024).

117. Gangadharan, P.; Kanchi, K.C.; Lou, H.H. Evaluation of the economic and environmental impact of combining dry reforming with steam reforming of methane. *Chem. Eng. Res. Des.* **2012**, *90*, 1956–1968. [CrossRef]

118. Rodriguez-Santiago, V. Utilization of carbon dioxide from coalfired power plant for the production of value-added products. In Proceedings of the 3rd Annual International Pittsburgh Coal Conference, PCC-Coal-Energy, Environment and Sustainable Development, Pittsburgh, PA, USA, 25–28 September 2006.

119. de Queiroz, F.; Araújo, Q.; de Medeiros, J.L.; Maria, R. CO_2 Utilization: A Process Systems Engineering Vision. In *CO2 Sequestration and Valorization*; InTech: London, UK, 2014. [CrossRef]

120. Ozkan, M.; Nayak, S.P.; Ruiz, A.D.; Jiang, W. Current status and pillars of direct air capture technologies. *IScience* **2022**, *25*, 103990. [CrossRef]

121. Kahle, L.C.S.; Roussière, T.; Maier, L.; Herrera Delgado, K.; Wasserschaff, G.; Schunk, S.A.; Deutschmann, O. Methane dry reforming at high temperature and elevated pressure: Impact of gas-phase reactions. *Ind. Eng. Chem. Res.* **2013**, *52*, 11920–11930. [CrossRef]

122. Ross, J.R.H. Natural gas reforming and CO_2 mitigation. *Catal. Today* **2005**, *100*, 151–158. [CrossRef]

123. Estes, D.P.; Copéret, C. The Role of Proton Transfer in Heterogeneous Transformations of Hydrocarbons. *Chimia* **2015**, *69*, 321. [CrossRef]

124. Koirala, R.; Buechel, R.; Krumeich, F.; Pratsinis, S.E.; Baiker, A. Oxidative dehydrogenation of ethane with CO_2 over flame-made Ga-loaded TiO_2. *ACS Catal.* **2015**, *5*, 690–702. [CrossRef]

125. Urlan, F.; Marcu, I.C.; Sandulescu, I. Oxidative dehydrogenation of n-butane over titanium pyrophosphate catalysts in the presence of carbon dioxide. *Catal. Commun.* **2008**, *9*, 2403–2406. [CrossRef]

126. Müller, K.; Baumgärtner, A.; Mokrushina, L.; Arlt, W. Increasing the Equilibrium Yield of Oxidative Dehydrogenation with CO_2 by Secondary Reactions. *Chem. Eng. Technol.* **2014**, *37*, 1261–1264. [CrossRef]

127. Wang, S.; Zhu, Z.H. Catalytic conversion of alkanes to olefins by carbon dioxide oxidative dehydrogenation—A review. *Energy Fuels* **2004**, *18*, 1126–1139. [CrossRef]

128. Ansari, M.B.; Park, S.E. Carbon dioxide utilization as a soft oxidant and promoter in catalysis. *Energy Environ. Sci.* **2012**, *5*, 9419–9437. [CrossRef]

129. MacDowell, N.; Florin, N.; Buchard, A.; Hallett, J.; Galindo, A.; Jackson, G.; Adjiman, C.S.; Williams, C.K.; Shah, N.; Fennell, P. An overview of CO_2 capture technologies. *Energy Environ. Sci.* **2010**, *3*, 1645–1669. [CrossRef]

130. Carbon Management: Implications for R&D in the Chemical Sciences and Technology—National Research Council, Division on Earth and Life Studies, Board on Chemical Sciences and Technology, Chemical Sciences Roundtable. Available online: https://books.google.com/books?hl=en&lr=&id=BQ1Lt4yEKskC&oi=fnd&pg=PT13&dq=Carbon+Management:+Implications+for+R+&+D+in+the+Chemical+Sciences+and+Technology+(A+Workshop+Report+to+the+Chemical+Sciences+Roundtable).&ots=MGzYopqM10&sig=VvEZ00ModX1zruDYWTQqN-PAvUs#v=onepage&q=Carbon%20Management:%20Implications%20for%20R%20&%20D%20in%20the%20Chemical%20Sciences%20and%20Technology%20(A%20Workshop%20Report%20to%20the%20Chemical%20Sciences%20Roundtable).&f=false (accessed on 29 January 2024).

131. Carbon Capture and Utilisation in the Green Economy. Available online: https://scholar.google.com/scholar?hl=en&as_sdt=0,44&q=Carbon+Capture+and+Utilisation+in+the+green+economy&btnG= (accessed on 30 January 2024).

132. Angunn, E.; Nada, A.; Gaëlle, B.C. Evaluation of Carbon Dioxide Utilisation Concepts: A Quick and Complete Methodology. *Energy Procedia* **2014**, *63*, 8010–8016. [CrossRef]

133. Meylan, F.D.; Moreau, V.; Erkman, S. CO_2 utilization in the perspective of industrial ecology, an overview. *J. CO2 Util.* **2015**, *12*, 101–108. [CrossRef]

134. Cuéllar-Franca, R.M.; Azapagic, A. Carbon capture, storage and utilisation technologies: A critical analysis and comparison of their life cycle environmental impacts. *J. CO2 Util.* **2015**, *9*, 82–102. [CrossRef]

135. Sanna, A.; Uibu, M.; Caramanna, G.; Kuusik, R.; Maroto-Valer, M.M. A review of mineral carbonation technologies to sequester CO_2. *Chem. Soc. Rev.* **2014**, *43*, 8049–8080. [CrossRef]

136. Pan, S.Y.; Chiang, A.; Chang, E.E.; Lin, Y.P.; Kim, H.; Chiang, P.C. An Innovative Approach to Integrated Carbon Mineralization and Waste Utilization: A Review. *Aerosol Air Qual. Res.* **2015**, *15*, 1072–1091. [CrossRef]

137. Special Report on Carbon Dioxide Capture and Storage. Available online: https://scholar.google.com/scholar?hl=en&as_sdt=0,44&q=Special+report+on+carbon+dioxide+capture+and+storage&btnG= (accessed on 29 January 2024).

138. Sanna, A.; Hall, M.R.; Maroto-Valer, M. Post-processing pathways in carbon capture and storage by mineral carbonation (CCSM) towards the introduction of carbon neutral materials. *Energy Environ. Sci.* **2012**, *5*, 7781–7796. [CrossRef]

139. Huijgen, W.J.J. Carbon Dioxide Sequestration by Mineral Carbonation. Ph.D. Thesis, Wageningen University, Wageningen, The Netherlands, 2007.

140. Matter, J.M.; Stute, M.; Snæbjörnsdottir, S.; Oelkers, E.H.; Gislason, S.R.; Aradottir, E.S.; Sigfusson, B.; Gunnarsson, I.; Sigurdardottir, H.; Gunnlaugsson, E.; et al. Rapid carbon mineralization for permanent disposal of anthropogenic carbon dioxide emissions. *Science (1979)* **2016**, *352*, 1312–1314. [CrossRef] [PubMed]

141. Bijl, D.L.; Bogaart, P.W.; Kram, T.; de Vries, B.J.M.; van Vuuren, D.P. Long-term water demand for electricity, industry and households. *Environ. Sci. Policy* **2016**, *55*, 75–86. [CrossRef]

142. McCutcheon, J.L.; McGinnis, R.L.; Elimelech, M. Ammonia-Carbon Dioxide Forward Osmosis Desalination; Water Conditioning & Purification: 2006. Available online: https://www.google.com/url?sa=t&source=web&rct=j&opi=89978449&url=https://elimelechlab.yale.edu/sites/default/files/files/wcp_oct2006.pdf&ved=2ahUKEwiwioyZv66IAxUl6ckDHfVUBFEQFnoECA0QAQ&usg=AOvVaw3BXR0RuR4mWx2avD5qObIM (accessed on 24 June 2024).

143. Max, M.D.; Sheps, K.; Tatro, S.R.; Brazel, L.; Osegovic, J.P. Seawater Desalination as A Beneficial Factor of CO_2 Sequestration. In Proceedings of the International Conference on Gas Hydrates (ICGH), Vancouver, BC, Canada, 6–10 July 2008. [CrossRef]

144. West, O.R.; Tsouris, C.; Liang, L. Method and Apparatus for Efficient Injection of CO2 in Oceans. U.S. Patent US6598407B2, 29 July 2003.

145. Dawoud, M.A. Environmental Impacts of Seawater Desalination: Arabian Gulf Case Study. *Int. J. Environ. Sustain.* **2012**, *1*, 22–37. [CrossRef]

146. Development of an Environmental Impact Assessment and Decision Support...—Sabine Latteman. Available online: https://books.google.com/books?hl=en&lr=&id=2kXLBQAAQBAJ&oi=fnd&pg=PP1&dq=Development+of+an+environmental+impact+assessment+and+decision+support+system+for+seawater+desalination+plants&ots=vYhITysE5M&sig=uHI8Zk7SiNppVoIwWHPFaodyHpU#v=onepage&q=Development%20of%20an%20environmental%20impact%20assessment%20and%20decision%20support%20system%20for%20seawater%20desalination%20plants&f=false (accessed on 29 January 2024).

147. Dindi, A.; Quang, D.V.; Abu-Zahra, M.R.M. Simultaneous carbon dioxide capture and utilization using thermal desalination reject brine. *Appl. Energy* **2015**, *154*, 298–308. [CrossRef]

148. Ampelli, C.; Perathoner, S.; Centi, G. CO_2 utilization: An enabling element to move to a resource- and energy-efficient chemical and fuel production. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **2015**, *373*, 20140177. [CrossRef]

149. Avila, A.M.; Yu, Z.; Fazli, S.; Sawada, J.A.; Kuznicki, S.M. Hydrogen-selective natural mordenite in a membrane reactor for ethane dehydrogenation. *Microporous Mesoporous Mater.* **2014**, *190*, 301–308. [CrossRef]

150. Buonomenna, M.G.; Yave, W.; Golemme, G. Some approaches for high performance polymer based membranes for gas separation: Block copolymers, carbon molecular sieves and mixed matrix membranes. *RSC Adv.* **2012**, *2*, 10745–10773. [CrossRef]

151. Chen, H.; Zhang, H.; Yan, Y. Catalytic combustion of volatile organic compounds over a structured zeolite membrane reactor. *Ind. Eng. Chem. Res.* **2013**, *52*, 12819–12826. [CrossRef]

152. Duyar, M.S.; Farrauto, R.J.; Castaldi, M.J.; Yegulalp, T.M. In Situ CO_2 Capture Using CaO/γ-Al$_2$O$_3$ Washcoated Monoliths for Sorption Enhanced Water Gas Shift Reaction. *Ind. Eng. Chem. Res.* **2014**, *53*, 1064–1072. [CrossRef]

153. Carvill, B.T.; Hufton, J.R.; Anand, M.; Sircar, S. Sorption-enhanced reaction process. *AIChE J.* **1996**, *42*, 2765–2772. [CrossRef]

154. Hufton, J.R.; Mayorga, S.; Sircar, S. Sorption-enhanced reaction process for hydrogen production. *AIChE J.* **1999**, *45*, 248–256. [CrossRef]

155. Stevens, R.W.; Shamsi, A.; Carpenter, S.; Siriwardane, R. Sorption-enhanced water gas shift reaction by sodium-promoted calcium oxides. *Fuel* **2010**, *89*, 1280–1286. [CrossRef]

156. Van Selow, E.R.; Cobden, P.D.; Verbraeken, P.A.; Hufton, J.R.; Van Den Brink, R.W. Carbon capture by sorption-enhanced water-gas shift reaction process using hydrotalcite-based material. *Ind. Eng. Chem. Res.* **2009**, *48*, 4184–4193. [CrossRef]

157. Minutillo, M.; Perna, A. A novel approach for treatment of CO_2 from fossil fired power plants. Part B: The energy suitability of integrated tri-reforming power plants (ITRPPs) for methanol production. *Int. J. Hydrog. Energy* **2010**, *35*, 7012–7020. [CrossRef]

158. Song, C.; Pan, W. Tri-reforming of methane: A novel concept for catalytic production of industrially useful synthesis gas with desired H_2/CO ratios. *Catal. Today* **2004**, *98*, 463–484. [CrossRef]

159. Duyar, M.S.; Wang, S.; Arellano-Treviño, M.A.; Farrauto, R.J. CO_2 utilization with a novel dual function material (DFM) for capture and catalytic conversion to synthetic natural gas: An update. *J. CO2 Util.* **2016**, *15*, 65–71. [CrossRef]

160. Lao, D.B.; Galan, B.R.; Linehan, J.C.; Heldebrant, D.J. The steps of activating a prospective CO_2 hydrogenation catalyst with combined CO_2 capture and reduction. *Green. Chem.* **2016**, *18*, 4871–4874. [CrossRef]

161. Reddy, K.J.; John, S.; Weber, H.; Argyle, M.D.; Bhattacharyya, P.; Taylor, D.T.; Christensen, M.; Foulke, T.; Fahlsing, P. Simultaneous capture and mineralization of coal combustion flue gas carbon dioxide (CO_2). *Energy Procedia* **2011**, *4*, 1574–1583. [CrossRef]

162. Al-Mamoori, A.; Krishnamurthy, A.; Rownaghi, A.A.; Rezaei, F. Carbon Capture and Utilization Update. *Energy Technol.* **2017**, *5*, 834–849. [CrossRef]