Carbon Dioxide Storage

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Carbon capture utilization and storage (CCUS) technologies are regarded as an economically feasible way to minimize greenhouse gas emissions. By chemically reacting CO_2 with calcium or magnesium-containing minerals, mineral carbonation technology creates stable carbonate compounds that do not require ongoing liability or monitoring. In addition, using industrial waste residues as a source of carbonate minerals appears as an option because they are less expensive and easily accessible close to CO_2 emitters and have higher reactivity than natural minerals. Among those geological formations for CO_2 storage, carbon microbubbles sequestration provides the economic leak-free option of carbon capture and storage.

carbon capture utilization and storage   carbon capture and storage CO_2 storage

1. Introduction

Since the beginning of the industrial revolution, the combustion of fossil fuels has resulted in the release of significant quantities of greenhouse gases such as carbon dioxide, nitrous oxide, methane, ozone, and chlorofluorocarbons [1]. As a gradual but direct result, global temperatures have risen by approximately 1.5 °C, primarily because of emissions of anthropogenic greenhouse gases [2][3]. Carbon dioxide (CO_2), a greenhouse gas generated in large quantities by human activity, is the leading contributor to climate change [4]. An increase in temperature of 1.5 °C or more can be expected to exert far-reaching and drastic consequences for water and food availability, human health, ecosystems, coastlines, and biodiversity [5]. Global warming, a crucially important environmental issue, has caused the loss of biodiversity, water, and land, while adversely affecting several sustainability criteria [6].

Several authoritative agencies have released the latest data related to carbon dioxide emissions. According to the International Energy Agency (IEA) analysis, carbon dioxide emissions of worldwide in 2021 rose by 6% to reach their highest-ever level of 36.3 billion tonnes, as the global economy recovered vigorously from the effects of the COVID-19 pandemic, there was a significant dependence on coal as the primary source of energy to support this growth. To limit global warming to approximately 1.5 °C (2.7°F), the Intergovernmental Panel on Climate Change (IPCC) scenarios suggest that worldwide emissions of greenhouse gases must be reduced by 43% before 2030 [3]. Additionally, the American National Oceanic and Atmospheric Administration reports that the current concentration of atmospheric CO_2 is 416 parts per million (ppm) and increasing at a rate of 2.8 ppm annually [7]. Therefore, reducing CO_2 emissions is necessary for human survival. Nevertheless, the world's energy demand is projected to increase by more than 28.6% by 2040 [8], indicating that brand-new energy sources including hydrogen, wind, and solar must replace fossil fuels. Even in light of that necessity, achieving such a transition in a short time is expected to be challenging [9].

As a practical method for lowering atmospheric CO_2 concentrations, carbon capture and storage (CCS) is at the center of attention [10]. Storage is a vital step in the development of CCS systems. Earlier review papers detailed numerous physicochemical techniques for effective CO_2 storage and emphasized the challenges posed by diverse techniques and initiatives [11][12][13][14]. For instance, many investigations have been reported of CO_2 storage techniques such as mineral carbonation (MC) [15], offshore storage [16], and geological storage [17]. However, Michael Economides, an energy specialist, claims that CCS, comprising numerous components such as collection, gathering, and injection, is an impractical solution for controlling CO_2 because of insurmountable hurdles related to physical needs and cost [18].

A similar strategy is employed for carbon capture, utilization, and storage (CCUS) that have gained significant attention as a promising approach to mitigating greenhouse gas emissions. While all three components (capture, utilization, and storage) are important, the utilization of captured carbon dioxide has been highlighted as a crucial element in the CCUS strategy. Carbon utilization not only reduces the net amount of carbon dioxide released into the atmosphere but also creates value-added products, thus providing economic incentives for the implementation of CCUS technologies [19]. **Table 1** provides a brief summary of the advantages and disadvantages of CCS and CCUS as well as a comparison of their CO_2 capture capabilities, which are general estimates and can vary depending on the specific technology and implementation used.

Table 1. Comparing CCS and CCUS.

Method	Advantages	Disadvantages	CO_2 Capture Value
CCS	Reduces carbon emissions from large point sources such as power plants and industrial processes	Requires significant energy and resources to capture, transport, and store CO_2; long-term stability of stored CO_2 and prevention of leakage are concerns	Can capture up to 90% of CO_2 emissions from the source
CCUS	In addition to reducing carbon emissions, captured CO_2 can be used in products such as chemicals and fuels, potentially creating a new revenue stream; utilization can reduce the overall cost of carbon capture	Utilization processes can require significant energy and resources; economic viability of utilization depends on various factors	Can capture up to 99% of CO_2 emissions from the source

According to a report by the International Energy Agency (IEA) [20], “utilizing captured carbon dioxide can be a game-changer for the economics of carbon capture, making it more viable for both power and industrial applications”. The report also notes that carbon utilization has the potential to reduce the cost of CCUS by up to 50%, depending on the technology used and the price of CO_2 emissions. Several carbon utilization pathways have been proposed and tested, including enhanced oil recovery, mineral carbonation, and the production of chemicals and fuels. For instance, carbon dioxide can be used to enhance the recovery of oil and gas from existing wells, a process known as enhanced oil recovery (EOR), which has been shown to be economically viable in certain regions. Another pathway is the mineral carbonation of silicate minerals, which involves the reaction of carbon dioxide with silicate minerals to produce stable carbonates. This approach has been demonstrated in pilot-scale projects and has the potential to permanently store carbon dioxide in a geological form. Additionally, captured carbon dioxide can be used as a feedstock for the production of chemicals and fuels, including methanol, urea, and dimethyl ether. A study by Biswal et al. [21] explored the potential of converting captured CO_2 into methanol, which is a valuable fuel and chemical intermediate. They found that integrating carbon capture with methanol production could significantly reduce CO_2 emissions while also generating economic benefits. Another study by Szima et al. [22] investigated the use of CO_2 in the production of synthetic natural gas (SNG) through a process called the Sabatier reaction. The study demonstrated the potential of CCUS-SNG to not only reduce CO_2 emissions but also contribute to energy security and resource utilization. Additionally, the utilization of CO_2 for the production of building materials, such as concrete, has gained attention in recent years. A study by Li et al. [23] investigated the use of CO_2 in the production of lightweight concrete, which has potential environmental and economic benefits. Overall, the utilization of CO_2 is a promising component of CCUS, offering both environmental and economic benefits. In conclusion, carbon utilization is a critical component of the CCUS strategy as it not only reduces greenhouse gas emissions but also provides economic incentives for the implementation of CCUS technologies. Consequently, until renewable energy is used more extensively, carbon capture utilization and storage (CCUS) technologies by converting captured CO_2 into valuable products are regarded as an economically feasible way to minimize greenhouse gas (GHG) emissions.

In a CCUS supply chain, CO_2 is collected and compressed at the source facility before being transported to a location for use or injection for geological sequestration. Reportedly, CCUS has the potential to cut global CO_2 emissions from the energy sector by 20% [24]. Although many studies have evaluated CCS or CCUS operations, few have considered storing CO_2 and industrial waste together in underground spaces, such as abandoned coal mines and Underground Coal Gasification (UCG) cavities.

2. CO_2 Storage Methods

This discussion offers an in-depth analysis of the relevant literature, advancements, and debates related to different CCUS methodologies. **Figure 1** portrays the main CO_2 storage methods which are commonly acknowledged as CCS/CCUS technologies. They have the capability of lowering CO_2 emissions. However, to achieve the predicted net-zero CO_2 emissions objective by 2050, their present worldwide deployment remains insufficient [25]. Various strategies for CO_2 sequestration including physical, biological, and chemical storage possibilities are being investigated because the captured CO_2 must eventually be stored to eliminate its effects [26][27]. Biological storage refers to the process by which living organisms absorb and store carbon, converting CO_2 from the atmosphere into organic matter through photosynthesis. This process is essential for regulating the carbon cycle and maintaining a stable climate. Biological storage includes the carbon sequestration in plants [2] and soil carbon sequestration [28]. Plants, algae, and other photosynthetic organisms play a key role in biological storage by converting CO_2 into organic compounds, such as carbohydrates and proteins [29]. These compounds can be stored within the organism's tissues or released into the soil, where they can be further broken down and stored as organic matter [30]. Physical storage includes geological storage [31][32] and ocean storage [33]. Mineral carbonation is a chemical storage method that involves the reaction of CO_2 with minerals [31]. Physical and chemical storage will be detailed in the following chapters. Carbon dioxide storage can be achieved through three main methods: (i) geological storage in deep geological formations, (ii) ocean storage in deep ocean water, and (iii) mineral storage in the form of mineral carbonates [31].

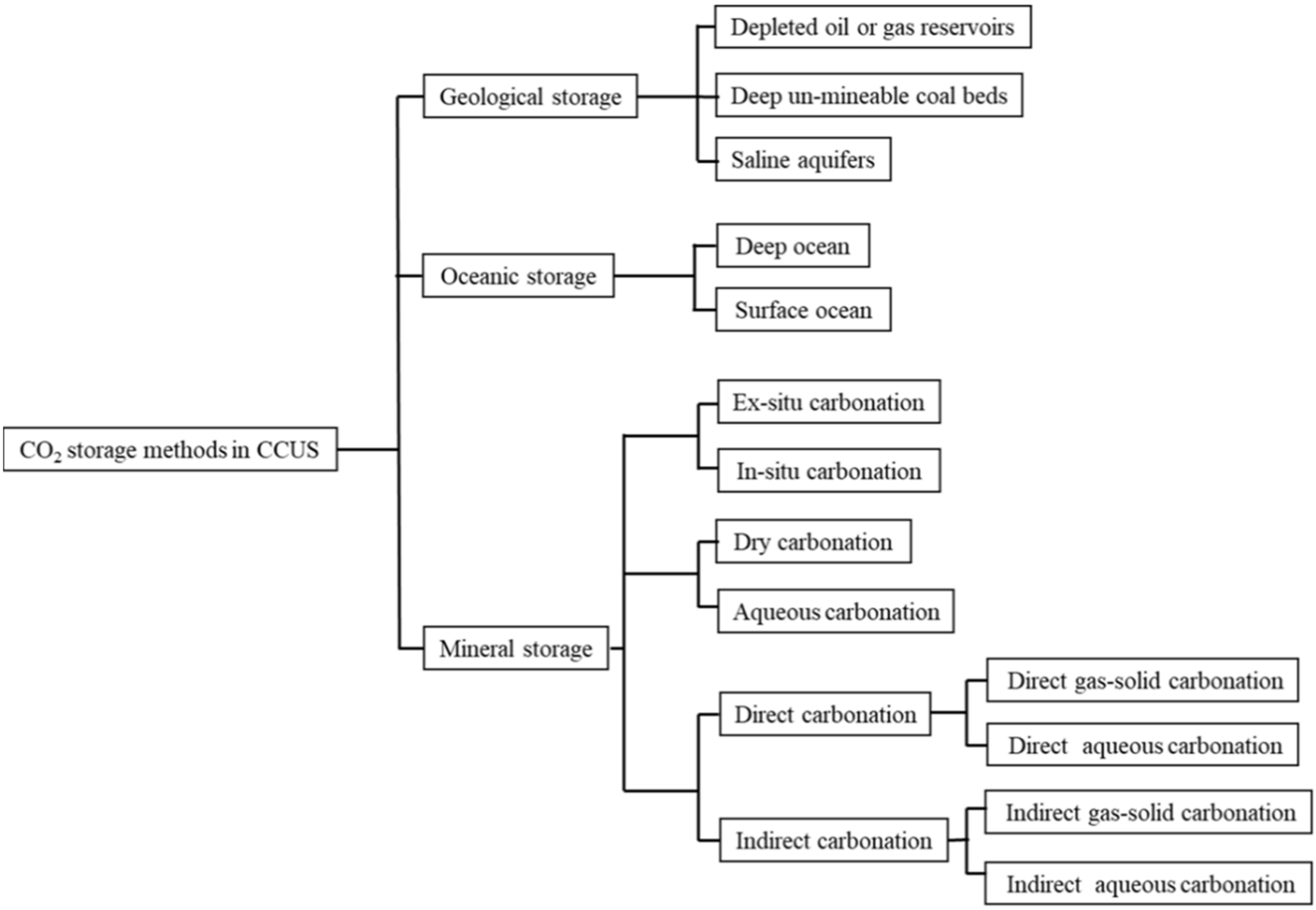

Figure 1. CO_2 storage methods.

2.1. Geological Storage

Similarly to the natural storage of fossil fuels in nature, CO_2 geological storage involves the injection of CO_2 into a suitable underground geological formation or stratum at a specific depth. During the last decade, reports of the literature describing investigations of geological CO_2 storage have increased considerably [34]. Over 1 million tonnes of CO_2 are now being stored at 14 different places throughout the world [35]. Depending on the research location, the estimated global CO_2 storage capacity ranges from 100 to 20,000 gigatons CO_2 [36]. Saline aquifers, deep unmineable coal beds, and depleted oil and gas reservoirs are considered the best places for CO_2 geological storage [31].

2.1.1. Depleted Oil or Gas Reservoirs

Geological storage is an extensively employed technique for enhanced oil and gas recovery (EOR/EGR) due to its potential for large-scale storage capacity [37][38]. In fact, depleted oil and gas reservoirs' storage of CO_2 is regarded as an extremely effective storage option, illustrating a few of its many benefits: (i) extensive prior research and exploration during hydrocarbon exploration stages, which has allowed for the determination of storage capacity; (ii) existing subterranean and surface infrastructure, such as pipelines and injection wells, that is useful for storage processes with minimal modification [39][40][41]; and (iii) the oil and gas industry's widespread usage of CO_2 injection as an EOR technology, which can be leveraged for storage processes [42].

For EOR, CO_2 is used to increase the reservoir pressure, thereby creating sufficient driving force to extract the remaining oil from active wells. Furthermore, the injection of CO_2 can be utilized to recover natural gas (methane, CH_4) from coal beds. The basic principle behind this method is that the introduction of CO_2 can displace CH_4 from the coal while simultaneously storing the CO_2 within the porous structure of the coal bed [43]. The injection of CO_2 for EOR is supported by mature technologies. Moreover, studies have investigated various aspects of the processes, including migration simulation [44], geochemical modeling [45], and leakage/risk assessment [46]. However, environmental considerations associated with EOR include the creation of massive volumes of water that might include radioactive materials and hazardous heavy metals [47].

2.1.2. Deep Unmineable Coal Beds

Coal bed methane (CBM) reservoirs are naturally occurring formations of coal that contain large amounts of methane gas trapped within the coal matrix. When coal bed methane is extracted, it not only removes the methane gas but also reduces the pressure within the coal seam. This pressure reduction can cause the release of CO_2 that is adsorbed onto the coal surface. This process is known as CO_2 desorption and can lead to the release of significant amounts of CO_2 into the atmosphere [48].

However, coal beds also have the potential to store large amounts of CO_2 through a process called CO_2 sequestration. This process involves injecting CO_2 into unmineable coal seams where it is adsorbed onto the coal surface, replacing methane gas. The CO_2 is then trapped within the coal matrix and stored underground for long periods of time, potentially mitigating the release of CO_2 into the atmosphere. The technique of CO_2 storage in coal seams involves utilizing the void space created by the removal of methane. A comprehensive review of this method was conducted by White et al. [43], which highlighted key issues such as estimation of potential storage capacity, storage integrity, physical and chemical processes, as well as environmental health and safety. The storage potential of deep unmineable coal beds for CO_2 sequestration is significant. In fact, coal beds have been estimated to have the potential to store over 500 gigatons of CO_2 globally. A study by Hu and Cheng [49] estimated the potential of CO_2 storage in deep unmineable coal seams in China to be 69.5 Gt. Similarly, another study by Liu et al. [50] estimated the CO_2 storage capacity in the Illinois Basin to be 66.7 Gt. Furthermore, coal beds are often located near power plants, which could provide a convenient source of CO_2 for sequestration.

The long-term storage stability of CO_2 in deep unmineable coal beds is dependent on several factors, such as the coal type, coal rank, depth, and pressure. Hu and Cheng [49] reported that deep coal seams with high-rank coal have higher CO_2 storage capacity and better storage stability due to their low permeability and high sorption capacity. Additionally, the geological sequestration of CO_2 in deep unmineable coal seams has been found to be effective in the long term, as reported by Bao et al. [51].

One of the primary technical advantages of CO_2 sequestration in deep unmineable coal beds is the existing infrastructure and knowledge from the coal bed methane industry. Additionally, CO_2 injection can enhance methane production, which can offset some of the costs associated with CO_2 sequestration [52]. Furthermore, the use of unmineable coal beds for CO_2 sequestration can also avoid potential environmental impacts associated with coal mining activities [51].

However, there are several challenges associated with CO_2 sequestration in deep unmineable coal beds. One of the main challenges is the potential for CO_2 leakage, which can occur due to faults or fractures in the surrounding rock formations [50]. Additionally, the costs associated with CO_2 injection, monitoring, and verification can be high. There is also the need for the development of regulatory frameworks and policies to ensure the safe and effective implementation of CO_2 sequestration in deep unmineable coal beds [51].

In summary, CO_2 sequestration in deep unmineable coal beds has significant potential for mitigating CO_2 emissions from power plants and other industrial sources. However, it also presents significant technical challenges that must be addressed to ensure the safety and effectiveness of this approach.

2.1.3. Saline Aquifers

Deep saline aquifers, located at depths of 700–1000 m below ground level, are known to contain high-salinity formation brines [53]. While these saline aquifers are not commercially valuable, they can serve as a useful storage site for injected CO_2 captured from the CCS process. Indeed, saline aquifers are considered an important option for CO_2 storage due to their vast storage capacity. It is estimated that they are capable of sequestering 10,000 gigatons (Gt) of CO_2, which is equivalent to the emissions from large stationary sources for over 100 years [54][55]. Saline aquifers, in contrast to other storage sites, often have a larger spatial distribution and broader regional coverage.

Saline aquifers have the potential to store up to 10,000 gigatons of CO_2, which is equivalent to 20–500% of the predicted emissions by 2050, as reported by Davison, Freund, and Smith [56]. According to Pruess et al. [57], the long-term CO_2 storage capacity in saline aquifers is approximately 30 kg/m^3. Another important advantage of these aquifers is that they are easily accessible from most existing CO_2 capture sites, which makes the CO_2 sequestration process much more cost-effective. Additionally, these aquifers are often highly mineralized and are not suitable for supplying drinking water, making them a viable option for CO_2 storage without compromising the availability of freshwater resources [56]. Rock porosity is a crucial factor for CO_2 sequestration, as it enables the injection and storage of CO_2 by displacing brine or gas from pore structures. Deep saline aquifers are typically abundant in both porosity and permeability, making them the most suitable locations for CO_2 storage [58]. Although saline aquifers have the potential to store a large amount of CO_2, there is still less knowledge available about their storage characteristics compared to other geological storage sites, such as coal seams and oil fields. Yang et al. [59] conducted a review on the characteristics of CO_2 sequestration in saline aquifers, including the behavior of CO_2 in different phases, the interactions of CO_2 with water and rock, and the mechanisms of CO_2 trapping, such as hydrodynamic trapping, residual trapping, solubility trapping, and mineral trapping [60][61][62]. Extensive investigations have been conducted on the parameters that influence the mineral trapping of CO_2 during its sequestration in brines [63]. Szulczewski et al. [64] assessed pressure buildup during injection and CO_2 entrapment within the pore spaces of deep saline aquifers to estimate CO2 storage capacity. Nevertheless, due to inadequate understanding of the geochemical behavior in saline aquifers, global CO_2 storage capacity estimates remain imprecise [65]. Economically, many saline aquifers are currently considered less desirable as a storage option due to the lack of necessary infrastructure, including injection wells, surface equipment, and pipelines, as well as the associated capital costs required for developing such infrastructure.

Although geological storage of CO_2 has the potential to significantly reduce greenhouse gas emissions, there are also several potential drawbacks and challenges associated with this method. One of the main concerns with geological storage is the possibility of CO_2 leakage [66]. While caprock formations are designed to prevent CO_2 from escaping, there is still a risk of leakage due to natural fractures or faults in the rock. In the event of a leakage, the stored CO_2 could potentially migrate to the surface and pose a risk to human health and the environment. Another challenge is that geological storage might entail risks such as geological structure deformation, underground water acidification, and increased incidence of earthquakes [67]. Additionally, there are also concerns around the cost and energy requirements of geological storage [66]. While this method has been used for decades in the oil and gas industry, it is still relatively expensive and energy intensive. There is also a need for the ongoing monitoring and maintenance of storage sites, which can add to the overall cost [68].

2.2. Oceanic Storage

The oceans constitute a crucially important natural carbon sink that absorbs excess CO_2. The exchange of CO_2 at the air–sea interface dissolves carbon, which is subsequently carried in seawater via the circulation of thermohaline. The physical conditions that affect ocean storage include temperature, salinity, and pressure. These conditions determine the solubility of CO_2 in seawater and the rate at which CO_2 can be transported to the deep ocean. In general, colder and saltier water can dissolve more CO_2 than warmer and fresher water. This means that the polar regions are particularly well suited for ocean storage, as they have colder and saltier water than other regions of the ocean [69]. Pressure is also an important factor in ocean storage, as it affects the solubility of CO_2 and the rate at which it can be transported to the deep ocean [70]. Additionally, CO_2 is transported to the deep ocean via the sinking of organic material, including phytoplankton, through the biological pump [27].

Efforts have been made to replicate natural processes for carbon sequestration through two mechanisms in the ocean. The first involves pumping CO_2 straight into the deep ocean without passing the mixed layer. Despite conversations among experts and entrepreneurs, there are currently no prospects for crediting carbon trapped in the ocean. Similarly to geological storage, oceanic carbon storage involves injecting CO_2 into the deep ocean, creating liquid CO_2 lakes through the high pressure and supercritical state. Captured CO_2 might be transferred via a pipeline or ship to the ocean or seafloor for discharge. Oceanic storage has a significant theoretical CO_2 storage capacity, as the world's deep ocean trenches have the potential to store vast amounts of CO_2. The Puerto Rico trench, for example, has the capacity to store 24,000 Gt of liquid CO_2 deeper than 7 km, and the Sunda trench, located below 6 km, has the potential to accommodate 19,000 Gt of liquid CO_2, surpassing the CO_2 yield from all current global fossil fuel reserves. However, concerns have been raised that the stored CO_2 might escape back into the atmosphere [71]. Hence, it requires careful monitoring to ensure that the CO_2 does not leak back into the atmosphere [72]. The second involves adding nutrients to the surface ocean to stimulate the biological pump. Ocean fertilization involves adding nutrients to the ocean to stimulate the growth of phytoplankton, which absorb CO_2 during photosynthesis. When the phytoplankton die, they sink to the bottom of the ocean, carrying the stored CO_2 with them [73].

On the opposite side, the injection of CO_2 into the ocean could cause seawater acidification, leading to harm to marine ecosystems and leading to potentially devastating effects on marine life. According to Caldeira and Wickett [74], ocean model predictions suggest that carbon dioxide emissions to the atmosphere and ocean will cause significant chemistry changes. Since the London Convention restricted ocean storage in 2007, research in this field has been significantly reduced with considering these possibilities of the above disadvantage [34].

2.3. Mineral Storage

Mineral sequestration techniques were initially proposed by Friedel [75], who suggested accelerating the carbonation process by using high-purity CO_2. Mineral carbonation (MC) is a promising technology for carbon capture and storage (CCS) that mimics the natural weathering processes. The process involves an exothermic reaction between CO_2 and alkaline earth-metal-bearing minerals and wastes, resulting in the formation of stable carbonate minerals [76][77][78]. Carbonates are more thermodynamically stable than CO_2, as their standard Gibbs free energy is lower. Therefore, they are considered as a more stable form of carbon [79]. The stability of carbonates suggests that CO_2 mineral storage offers a secure and long-term solution for storing CO_2 without the need for continuous monitoring. Compared to other carbon storage methods, mineral carbonation through the reaction of CO_2 with Ca and Mg-bearing minerals, either naturally or industrially, offers several unique advantages. These include excellent long-term stability of CO_2, the creation of value-added products through the carbonation process, and the potential for in situ application by various industries [80][81].

The literature related to MC is extensive. Numerous studies have been conducted and reviewed regarding the carbon sequestration process using mineral carbonation [82]. Reviews conducted by Sipilä et al. [83] and Huijgen et al. [84] have extensively examined the initial developments in this field until 2006. A review presented by Torróntegui et al. [85] has covered relevant studies until 2010. An overview of the growth of MC of industrial wastes was presented by Bodor et al. [86]. Numerous reviews have covered the evolution and contemporary advances of MC extensively, even describing the use of different feedstock materials [82][87][88]. Moreover, notable reviews explained the MC of ultramafic mine deposits [89], steel-making waste [90], fly ash [91], and pH swing processes [92].

Recently, separate reviews of the energy costs and carbon footprints associated with various MC routes were presented by Naraharisetti et al. [93] and Ncongwane et al. [94]. However, concerns have arisen about the techno-economic aspects of many earlier studies [95][96]. **Table 2** presents the estimated CO_2 storage capacities of the methods explained above.

Table 2. Estimated CO_2 storage capacity [97].

Option	Gigatons of Carbon (GTC)
Depleted oil or gas reservoirs	180–250
Deep unmineable coal beds	1–55
Saline aquifers	275–2750
Ocean storage	>5000
Mineral carbonation	Very large

3. Simultaneous Injection of CO_2 and Industrial Waste

Abandoned coal mines refer to the production mines and mining areas where a certain mineral resource either has been depleted, is on the brink of depletion, has lost its economic value for mining, or fails to meet environmental protection standards for mining [98]. Most coal mines around the world are known to use the traditional longwall mining method introduced in the 19th century [99]. Longwall panel mining involves the progressive removal of coal from a rectangular area, resulting in the collapse of the roof and the formation of a goaf. On the other hand, the Underground Coal Gasification (UCG) process creates underground voids through the gasification of coal [100]. When UCG or mining activities have been conducted at considerable depths, the storage of CO_2 in these artificial high-permeability zones becomes an appealing option [101]. Subsidence of the ground above the goaf endangers the formation of cracks from which CO_2 might leak upward. Considering the risks of leakage, carbon dioxide can be stored in the form of microbubbles because CO_2 injected as microbubbles not only dissolves rapidly in water: it is also little affected by buoyancy. Furthermore, the density of CO_2 when dissolved in water is greater than that of groundwater, thereby reducing the risk of upward leakage of CO_2 [102].

This section presents a method of combining underground storage and mineral storage: CO_2 microbubble water and industrial waste are injected into mined-out areas (closed underground coal mines or goaf after UCG) to fix carbon dioxide permanently, as shown in Figure 2. This method was tested in an underground abandoned coal mine during August 2022 in Mikasa City, Japan [103], as shown in Figure 3. The storage concept for CO_2 and

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industrial wastes, presented herein, offers a synergetic approach to stabilize the mined-out strata mechanical state for the mitigation of mining subsidence and providing an alternative course for the unfavorable disposal of industrial wastes.

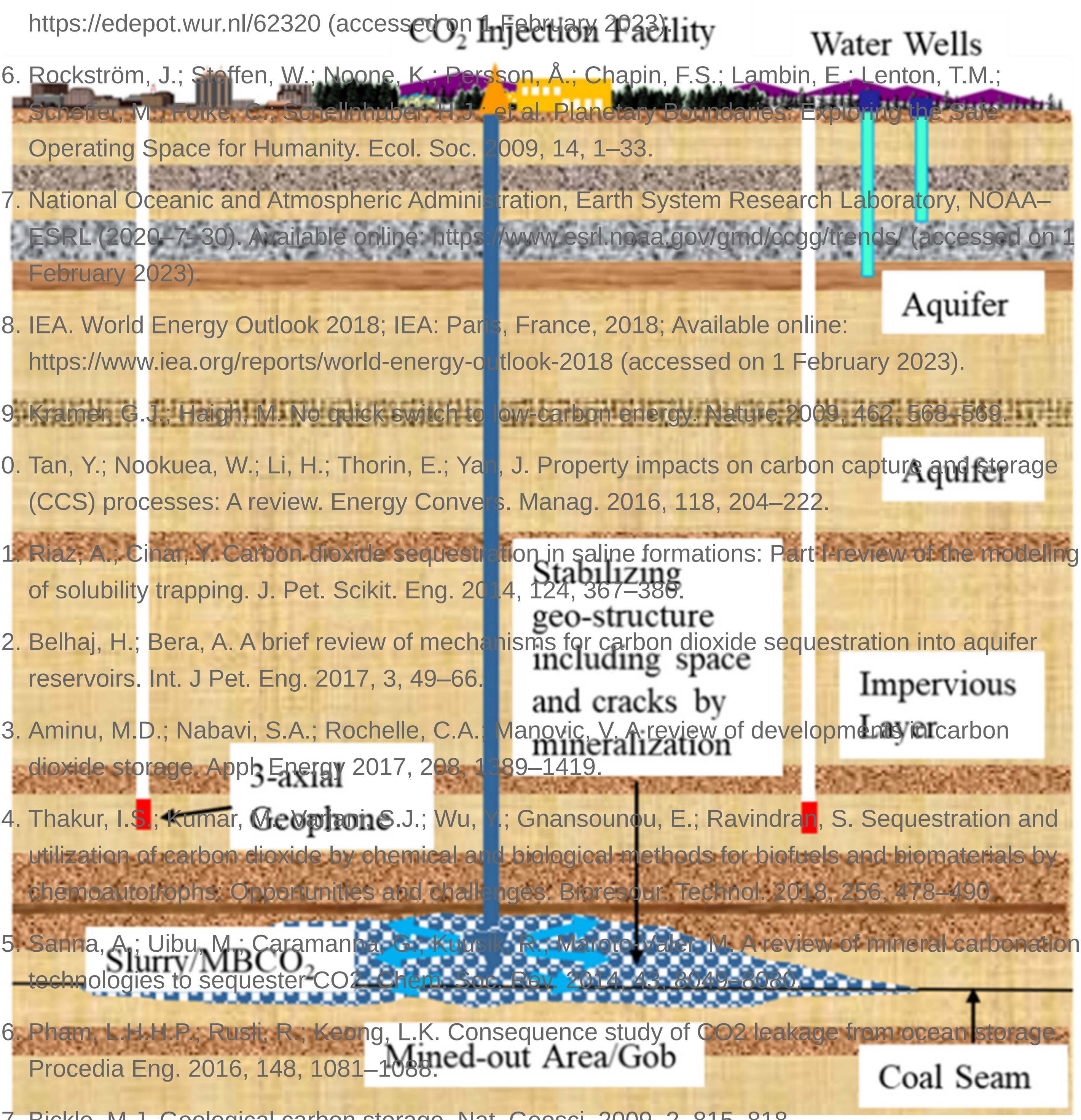

Figure 2. CO_2 storage schematic diagram.

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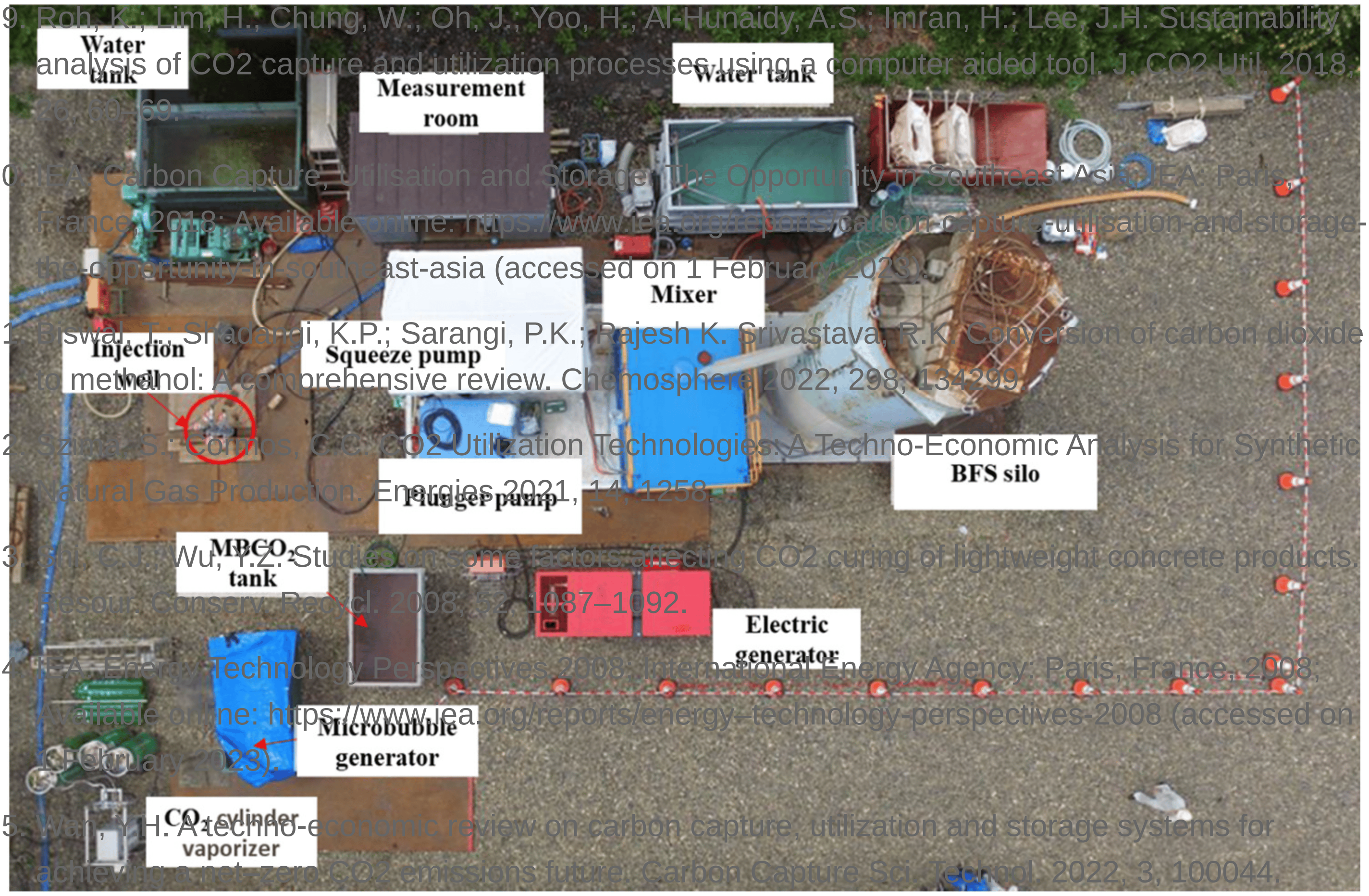

Figure 3. Injection site photograph.

A conceptual diagram of injection test equipment is portrayed in Figure 4. Because different injection materials share one injection well, two injection connecting pipes and corresponding valves for water/$MBCO_2$ and slurry on both sides of the wellhead are used. Using this configuration of the apparatus, slurry and water/$MBCO_2$ can be injected alternately according to the actual circumstances at the site. During and after the injection, the water quality of the river and groundwater near the injection well were analyzed, the carbon dioxide concentration in the injection well was monitored, and the micro-earthquake was monitored using a three-axial geophone. About 75 m^3 of water, 23 m^3 of $MBCO_2$, and 80 m^3 of slurry were injected during the entire injection stage. Findings obtained two months after completion of the injection test indicate that the permeability coefficient decreased greatly compared to that before injection, reflecting the solidification of the slurry in the fracture area of the injection layer.

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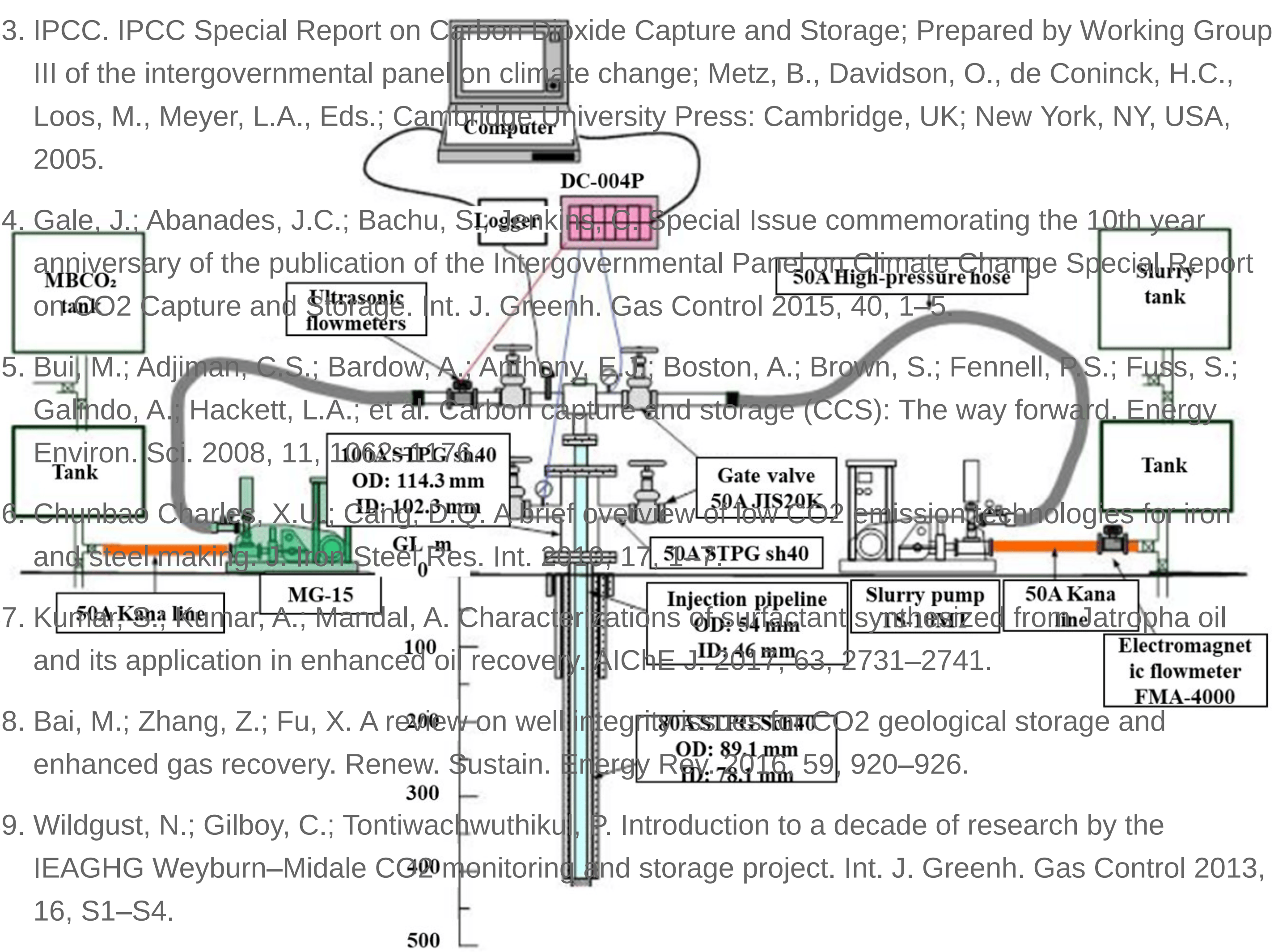

Figure 4. Conceptual diagram of injection test equipment.

4. Conclusions

The sections above presented a discussion of difficulties of greenhouse gas emissions attributable to the use of fossil fuels and the urgent need to reduce their use to constrain global warming. Carbon capture and storage (CCS) and carbon capture, utilization, and storage (CCUS) are garnering large amounts of attention as viable techniques to reduce CO_2 concentrations. Researchers specifically examined the latter approach, CCUS, where CO_2 is captured and used rather than only stored. Researchers presented analyses of the relevant literature and advancements in different CCUS methodologies, including physical, biological, and chemical storage possibilities. The storage of CO_2 can be accomplished in three main ways: geological storage, ocean storage, and mineral storage. The benefits and shortcomings of each method are discussed. Finally, Researchers introduced a method of simultaneous injection of CO_2 and industrial wastes into an underground goaf for mineralization, which is anticipated as a viable CCUS solution.

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