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A Review of CO_2 Marine Geological Sequestration

Xiang Sun [1], **Anran Shang** [2,3], **Peng Wu** [2,3], **Tao Liu** [2,3] **and Yanghui Li** [2,3,*]

[1] Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan 430071, China; xsun@whrsm.ac.cn
[2] Department of Energy and Power Engineering, Dalian University of Technology, Dalian 116024, China; wupeng@dlut.edu.cn (P.W.)
[3] Key Laboratory of Ocean Energy Utilization and Energy Conservation of Ministry of Education, Dalian University of Technology, Dalian 116024, China
* Correspondence: liy@dlut.edu.cn

Abstract: Carbon dioxide (CO_2) sequestration plays a crucial role in reducing the levels of atmospheric CO_2 and mitigating the harmful effects of global warming. Among the various CO_2 sequestration technologies, CO_2 marine geological sequestration emerges as a safer and more efficient alternative compared with traditional terrestrial geological sequestration. This is highly attributed to its expansive potential, safe distance from aquifers, and stable temperature and pressure conditions. This paper reviews and evaluates the main CO_2 marine geological sequestration technologies, including CO_2 sequestrations in shallow marine sediments, CO_2, sub-seabed aquifers, and CO_2-CH_4 replacement. The goal of this paper is to shed light on the mechanism, potential, and challenges of each technology. Given the importance of safety in CO_2 sequestration, this review also explores the potential adverse effects of CO_2 leakage from reservoirs, particularly its impact on marine environments. Finally, we discuss potential development trends in CO_2 marine geological technology.

Keywords: CO_2 marine geological sequestration; sequestration mechanism; Marine environment

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1. Introduction

With the continuous increase of carbon emissions, the global environment is gradually warming, and extreme weather frequently occurs, causing large-scale disasters such as drought, flood, and haze [1]. CO_2 is the main greenhouse gas, and it is important to control its atmospheric content so as to prohibit climate warming. CCS (Carbon Capture and Sequestration) technology is used to capture CO_2 generated in industrial processes and store it in reservoirs for a long time to reduce CO_2 emissions into the atmosphere [2–4]. CO_2 sequestration, as a core part of CCS technology, determines the path of CO_2 from being released into the atmosphere, thereby efficiently mitigating the greenhouse effect [5]. Figure 1 shows China's annual CO_2 emission is as high as 27% of the global total amount. In order to achieve the carbon emissions peak in 2030 and carbon neutrality in 2060, it is crucial to further develop CO_2 sequestration technology [6].

Traditional territorial geological sequestration involves a variety of methods, including CO_2-enhanced oil and natural gas fields [7–9], CO_2 sequestration in coal beds [10–12], saline aquifers [13], abandoned oil or gas fields [14], frozen soil [15], and enhanced geothermal systems [16]. Each method has its own limitations. For instance, CO_2-enhanced oil and natural gas fields, as well as CO_2 sequestration in abandoned oil and gas fields, have limited sequestration capacity due to the finite resource reserves of the exploitation area. The availability of these methods is low, and their application is restricted to specific exploitation areas, resulting in a constrained sequestration constituency [17]. In the case of saline aquifers, frozen soil, and enhanced geothermal systems, challenges arise from the need for deep underground well drilling, high costs, and the complex geological conditions in the deep strata. Consequently, the evaluation of geological characteristics and sequestration capacity remains insufficient [18]. Furthermore, supercritical CO_2 exhibits high buoyancy and tends to accumulate at the interface between saline aquifers and cap layers. Over time, this accumulation may induce seismic activity, which adversely affects sequestration stability [19].

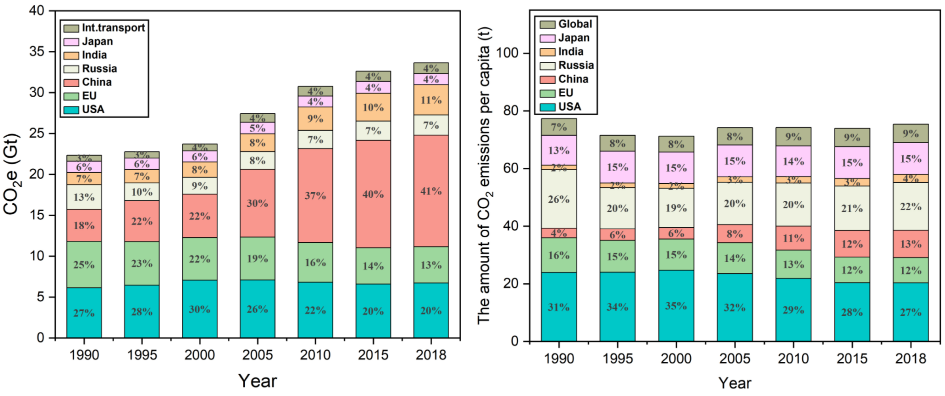

Figure 1. CO_2 emissions of major global carbon emitters, accumulated amout per year (left) and the amout per capita per year (right) [20].

Considering these challenges, Marchetti [21] first proposed the innovative concept of CO_2 marine sequestration in 1997. He suggested that CO_2 should be directly injected into deep and dense seawater under low temperature and high-pressure conditions, estimating that the ocean could seal CO_2 for thousands of years. This idea attracted widespread attention among scholars worldwide. However, direct dismission of CO_2 into the seawater would seriously impact the ecological environment of the ocean. Therefore, three creative marine geological sequestration methods are proposed to sequestrate CO_2 in the ocean area, including: sequestrations in shallow sediment, sub-seabed aquifers, and CO_2-CH_4 replacement. Zhao and Ikamura [3] published an article on carbon capture utilization and storage (CCUS) technologies, which are regarded as an economically feasible way to minimize greenhouse gas emissions. They also discussed the various aspects of CCUS. Each of these methods offers unique advantages and overcomes some of the limitations associated with traditional territorial geological sequestration technologies.

This paper investigates the storage mechanisms, capabilities, and main status related to CO_2 marine geological storage technologies. Existing problems in these technologies are summarized and their technical complexities are clarified. This paper also puts forward the related solutions to solve these problems in the future. The overall goal of this paper is to provide a summary of the pros and cons of CO_2 marine geological storage technologies, which will guide the development of the technologies, ensuring that they are both effective and environmentally friendly.

2. Overview of CO_2 Marine Geological Sequestration

CO_2 marine geological sequestration is a sophisticated technology that addresses the issue of anthropogenic climate change by capturing CO_2, a byproduct of industrial processes, and subsequently storing it in marine geological environments [17]. The advancement of this technology has been continuing, positioning it as a potential method for achieving carbon neutrality goals, first proposed by Marchetti [21]. Oceans, covering over 70% of the Earth's surface, provide a substantial theoretical sequestration capacity ranging from 2 to 13 trillion tons, making them a highly advantageous environment for large-scale CO_2 storage.

Direct sequestration of CO_2 into specific marine sedimentary strata has been demonstrated to effectively counteract the buoyancy of the gas, minimizing the risk of escape [22]. Researchers such as Fujioka et al. [23] thought that the deep seafloor offers an ideal geological space for CO_2 sequestration in both liquid and hydrate states. Haszeldine et al. [24] proposed that, in comparison to alternative methods, seabed sequestration has advantages in terms of safety, reliability, and ease of monitoring, further emphasizing the potential of this technology.

Despite the numerous advantages associated with CO_2 marine geological sequestration, it is crucial to acknowledge its limitations. One primary concern is that the method is not a permanent solution, as leakage can still occur, potentially leading to detrimental effects on marine organisms and the environment. This challenge highlights the primary importance of robust CO_2 monitoring technology in reducing risks. Additionally, the feasibility of implementing CO_2 marine geological sequestration technology varies across regions, as some areas present more favorable conditions for its application than others [25].

China has recognized the potential of marine geological sequestration technology in addressing its carbon emissions and has actively pursued studies on its feasibility within the country [25]. Researchers such as Chun et al. [26] have identified offshore basins, including the Pearl River Mouth and Beibu Gulf, as promising locations for CO_2 sequestration. In August 2021, China took a significant step forward by launching an offshore CO_2 demonstration project, which marked a major milestone in the advancement of the country's offshore CO_2 marine geological sequestration technology [27]. This effort demonstrates the commitment of China to leveraging the technology as a vital support in achieving its ambitious carbon neutralization goals by 2060.

3. Advantages and Disadvantages of CO_2 Marine Geological Sequestration Methods

Compared with CO_2 direct seawater sequestration, CO_2 marine geological sequestration is a more feasible and economical method. Moreover, it maintains geomechanical stability and reduces the risk of seabed landslides and geological disasters, thereby protecting marine ecosystems and their biodiversity. CO_2 marine geological sequestration can be roughly classified into three principal categories, including: CO_2 sequestrations in shallow marine sediments, a sub-seabed aquifer, and CO_2-CH_4 replacement. Figure 2 shows the physical model of CO_2 marine geological sequestration. In the shallow part of the CO_2 reservoir, hydrates are formed to prevent the leakage of CO_2. In the middle part of the reservoir, CO_2 can be trapped by gravity and flow downward to the deeper formations. In a deep reservoir, CO_2 may exist in a super-critical state and form a plume flow in the pore network of the reservoir. It requires a proper permeability of the reservoir formations to store and migrate the flow.

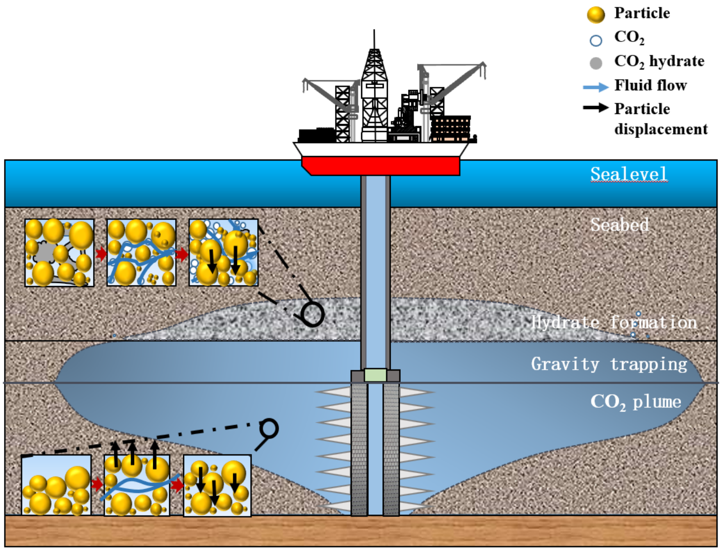

Figure 2. Physical model of CO_2 marine geological sequestration: in the shallow sediments, hydrates are formed to prevent the leakage of CO_2, which can be used as a caprock for the CO_2 reservoir. Beneath the hydrate caprock, CO_2 can be trapped by gravity and flow downward to the deeper formations. In a deep reservoir, CO_2 exists in a super-critical state and forms a plume flow in the reservoir.

3.1. Sequestration as Hydrate in Shallow Sediment

CO_2 sequestration in shallow marine sediments represents a distinctive CCS strategy, which notably diverges from conventional geological sequestration. This innovative approach entails the extraction of CO_2 from emission sources, followed by its injection beneath the mud line of seabed sediment within a depth of approximately 300 m from the seabed surface. When the stored seawater surpasses a depth of 2800 m, liquid CO_2 exhibits greater density than seawater, thereby being stored within sediment pores [28]. Meanwhile, under specific temperature and pressure conditions, CO_2 and water molecules interact to form hydrates within the sediment pores, which is called hydrate-based CO_2 sequestration (HCS), and Equation 1 shows the equation describing the chemical reaction of hydrate formation:

$$\mathrm{n_h H_2O + CO_2 = CO_2 \cdot n_h H_2O} \tag{1}$$

In the equation, n_h is the hydration number, which is ideally 5.7. Under standard conditions, 1 m^3 of hydrate can store 160–180 m^3 of CO_2 [29]. These hydrates play a crucial role in effectively capturing CO_2, minimizing sedimentary porosity, and inhibiting CO_2 escape, ultimately generating a relatively stable cap layer [22].

CO_2 sequestration in shallow marine sediments offers several distinct advantages over traditional geological sequestration. In geological sequestration, CO_2 exhibits buoyancy, which causes it to accumulate at the interface between saltwater and cap layers, potentially inducing seismic activity and undermining the stability of the sequestration process [19]. Additionally, geological sequestration requires extensive drilling, which increases the risk of CO_2 leakage following the injection process [30]. In contrast, sequestration in seabed sediments leverages the abundant pore space and unconsolidated skeleton structure of sediments, negating the need for complex drilling technology and reducing both costs and the potential for CO_2 leakage [31]. Furthermore, the high permeability of CO_2 facilitates its dispersion to remote areas from the injection site, resulting in enhanced sequestration efficiency [32]. By combining the negative buoyancy zone (NBZ) and hydrate forming zone (HFZ) within the sediment, an effective sequestration trap can be established, ensuring the safety, commercial viability, and scalability of this novel CCS approach [33,34]. To predict the leakage, monitoring technology is applied for safe sequestration, and seabed node seismic monitoring is used to detect CO_2 migration [35,36].

Despite its huge potential, CO_2 sequestration in shallow marine sediments faces several challenges, including the relatively rapid formation of CO_2 hydrate in the sediment layer. This process reduces the porosity and permeability of the sediment, inhibiting the injection and transport of CO_2, and subsequently reducing sequestration efficiency. To address this limitation, researchers have proposed the addition of nitrogen (N_2) to the CO_2 stream, which can decelerate hydrate formation and minimize blockage. Hassanpouryouzband et al. [37] proved that injecting a certain proportion of CO_2-N_2 into the sedimentary layer can promote the formation of CO_2 hydrate. When the temperature of the porous medium rises, N_2 hydrate will decompose ahead of the sequestration of CO_2 hydrate resulting in a longer and more stable sequestration. Yu et al. [38] carried out a numerical simulation of the injection of single CO_2 and CO_2-N_2 mixture into a single wellbore installed in the seabed sediment. Their results showed that the injection of CO_2-N_2 mixture improved the CO_2 sequestration efficiency while maintaining a relatively small deformation. This study emphasized the importance of injection capacity and the hydrate formation rate for the presence of CO_2 as a solid hydrate in seafloor sediments. Therefore, the addition of N_2 can accelerate the efficiency of CO_2 sequestration in shallow sediments, extending the period of the sequestration and keeping the mechanical properties of the seabed relatively stable.

The stability and security of CO_2 reservoirs in shallow sediments remain a concern. The process of CO_2 injection and migration can alter the skeleton of sediment structure and shear strength, leading to a dynamic disturbance of the CO_2 reservoir [39]. Changes in pore structure can negatively impact CO_2 transport, modifying the porosity and permeability of the reservoir, and generating uncertainty in the CO_2 sealing volume and sequestration efficiency [40]. In addition, over time, the CO_2 hydrate may partially dissolve or decompose, triggering sediment creep, reducing strength and stiffness, ultimately affecting the integrity and stability of the cap [41]. It is, therefore, necessary to develop a geotechnical theory and a coupled multiphysical modeling framework suitable for CO_2 marine geological sequestration to ensure the successful execution of efficient and safe CCS projects in an increasingly ecologically conscious global landscape.

3.2. Sequestration in Sub-Seabed Aquifers

The geological structure of the seafloor, which extends from the terrestrial landscape, offers an opportunity to harness the potential of sub-seabed aquifers for CO_2 sequestration. This method involves injecting captured CO_2 into rock strata containing groundwater with a closed structure beneath the seabed using a wellbore [22]. The sequestration mechanism within these aquifers relies on several key factors. CO_2 is introduced at high pressure, occupying space within the aquifer. Due to density differences, the lighter gas floats on the cap rock, while some CO_2 is trapped in a dissolved state within a brine solution. Another portion of the CO_2 mineralizes with water and hypertonic rocks, eventually forming carbonate trapped in the rock layers [42]. However, this mineralization process takes thousands of years, making the first two mechanisms the primary methods of sequestration [43].

Sub-seabed aquifers are considered the most promising option among marine geological sequestration technologies due to their potential and feasibility. One of the main reasons is the presence of sediment layers between the aquifers and the seabed surface, which are conducive to the formation of CO_2 hydrates [44]. These hydrates provide a secondary barrier to CO_2 leakage in the event of cap rock cracks or faults. Furthermore, when the density of CO_2 reaches 90% of seawater under specific temperature and pressure conditions, the gas becomes immobile due to gravity and capillary action, further ensuring the stability of sequestration in sub-seabed aquifer [28].

However, not all sub-seabed aquifers are suitable for CO_2 sequestration. To be considered suitable, an aquifer must have high porosity and permeability, as well as a stable hydrate or low permeability clay layer and a soft mud cap layer to prevent leakage [45]. Additionally, the reservoir should contain high permeability sandstone that can directly store CO_2 and react with it to rapidly form stable carbonate. Among various sub-seabed aquifers, basalt is an excellent candidate for sequestration [46]. First, basalt is highly porous and permeable because it erupts from volcanic ridges in all of the world's oceans, forming pillow lava and lava flows on the seafloor, which are buried over time, creating highly permeable aquifers within the oceanic crust. Secondly, basalt aquifer for geological CO_2 sequestration arises from providing multiple physical/chemical trapping mechanisms magnesium, which makes deep-sea basalt acts as a natural, in situ weathering reactor. Moreover, basalt aquifer has a high iron content, reaction rate, and large reservoir capacities, which makes it an excellent reservoir for CO_2 sequestration [45,47,48]. Its dense cap layer on the ocean crust further enhances its suitability [49]. Luhmann et al. [47] found that the flow rate had a significant effect on the permeability and the outlet fluid chemistry of the basalt cores. At a higher flow rate, permeability increased and Fe, Mg, and Si concentrations were relatively stable. At a lower flow rate, permeability decreased and Fe, Mg, and Si concentrations showed complex trends. The authors also observed secondary mineralization of Al- and Si-rich phases and an Fe2O3-rich phase on the post-experimental cores. They suggested that siderite formation was thermodynamically favorable at low pH, and that alkali metals were highly mobile during fluid-basalt interaction. Goldberg et al. [45] studied the fluid-basalt interaction in CO_2-rich systems and its implications for carbon sequestration and reservoir properties in basaltic formations. They highlighted the importance of flow rate, pH, and CO_2 concentration on the alteration processes and the reservoir properties. They also suggested that the composition of secondary carbonates could be used to infer the environmental conditions during their formation. Goldberg et. al. [48] discussed the potential of deep-sea basalt sites for carbon sequestration and proposed a global site assessment strategy to identify the most secure oceanic basalt sites that provided all trapping mechanisms. They suggested that deep-sea basalt sites have several advantages over other carbon sequestration options, such as terrestrial storage and oceanic injection. They also highlighted the importance of understanding the geological, hydrological, and biological factors that affect the carbon sequestration capacity of deep-sea basalt sites.

Despite the potential benefits of sequestration in sub-seabed aquifers, many factors such as temperature distribution, geothermal gradient, sediment thickness, and reservoir porosity and permeability can limit its effectiveness. One successful example of the sequestration in sub-seabed aquifer is Norway's Sleipner field CCS project in the North Sea, which has sequestrated over 8 million tons of CO_2 into the subsea brackish water layer since its inception in August 1996 [44]. This sequestration project used an alkamine solvent to absorb CO_2 from natural gas and stored it in the Utsira formation, which consists of a 200–300 m thick sandstone reservoir with high porosity and permeability and a relatively thin shale interval (1–2 m thick) under the seabed at a depth of 1000 m, and it is covered by a 250 m thick shale cap, which can effectively avoid the leakage of CO_2 from the storage layer. The Sleipner project as a whole has two distinctive features: a very regular and stable injection history, and continuous geophysical monitoring. These factors have made Norway's Sleipner field one of the most successful CO_2 marine geological sequestration projects in the world [50,51]. To maximize the potential of this promising CO_2 sequestration method, it is essential to address these limiting factors and develop a comprehensive understanding of the geological and environmental conditions, such as geothermal gradient, reservoir porosity, and permeability, that contribute to successful sequestration. Temperature distribution played a crucial role in the Sleipner field CCS project. The injection of CO_2 into the Utsira formation required an understanding of the temperature distribution within the reservoir. The temperature distribution affected the behavior of CO_2 and its interaction with the surrounding rock formations [52]. This study compared the geomechanical deformation induced by CO_2 storage at Sleipner, Weyburn, and In Salah, highlighting the importance of temperature distribution in the success of the CCS project [52]. Sediment thickness was another important factor in the success of the Sleipner field CCS project. The thickness of the sediment layer affected the storage capacity and containment of CO_2 within the reservoir. A thicker sediment layer provided a larger storage volume for CO_2 [53]. The study by Pegler et al. [54] estimated the parameters for the ongoing CCS operation at Sleipner, including sediment thickness, to understand the fluid migration between confined aquifers. Reservoir porosity and permeability were critical factors in the Sleipner field CCS project. Porosity referred to the volume of empty spaces within the reservoir rock, while permeability referred to the ability of fluids to flow through the rock. High porosity and permeability were desirable for efficient CO_2 storage and injection [55]. The study by Shahkarami et al. [56] modeled the pressure and saturation distribution in a CO_2 storage project, highlighting the importance of reservoir porosity and permeability.

Moreover, continued research, development, and collaboration among stakeholders are crucial for optimizing this technology and ensuring its sustainable integration into global CCS strategies.

3.3. CO_2-CH_4 Replacement Sequestration

Methane hydrate reserves on Earth are extensive, with a vast amount present in the world's oceans, sufficient to supply human consumption for approximately 1000 years. Traditionally, the extraction of natural gas hydrate (NGH) has been dependent on the method of direct exploitation. However, this approach has been associated with serious marine geological disasters, such as seabed settlement, landslides, borehole breakage, and gas leakage, which pose significant risks to the surrounding environment [57–59]. In 1996, Ohgaki et al. [60] introduced a concept of replacing CH_4 in hydrate-bearing sediments (HBS) with CO_2. Subsequently, Wilder [61] and Kim [62] provided evidence supporting the theoretical feasibility of this innovative process by conducting an in-depth analysis and comparison of the phase equilibrium curves of methane and CO_2 hydrates, as shown in

Figure 3. The figure shows that the yellow zone is suitable for hydrate formation under 1200 m depth in the ocean, and the CO_2-CH_4 replacement sequestration occurs here. The replacement reaction is also influenced by the geothermal gradient. The replacement rate is very low when the replacement pressure is higher than the equilibrium pressure of the CH_4 hydrate. It is difficult to change the temperature of sediment but easy to reduce its pressure using a depressurizing well. Their findings revealed that the pressure required for CO_2 hydrate formation is lower than that for NGH at the same temperature. Furthermore, CO_2 demonstrates a stronger affinity for water than CH_4. As a result, the replacement process involving CH_4 and CO_2 has been identified as spontaneous and exothermic in nature, which promotes the decomposition of NGH and accelerates the overall replacement process in turn [63]. Espinoza et al. [64] utilized seismic wave monitoring technology to study the process of replacing CO_2 with NGH in HBS. Their research indicated that the replacement process of CO_2 and CH_4 hydrate did not induce any changes in sedimentary strength. Moreover, CO_2 injection was found to maintain the stability of the formation structure. Despite these encouraging findings, both the rate of the CO_2 replacement reaction and the rate of gas hydrate sequestration are relatively low, with a maximum theoretical value of only 75%.

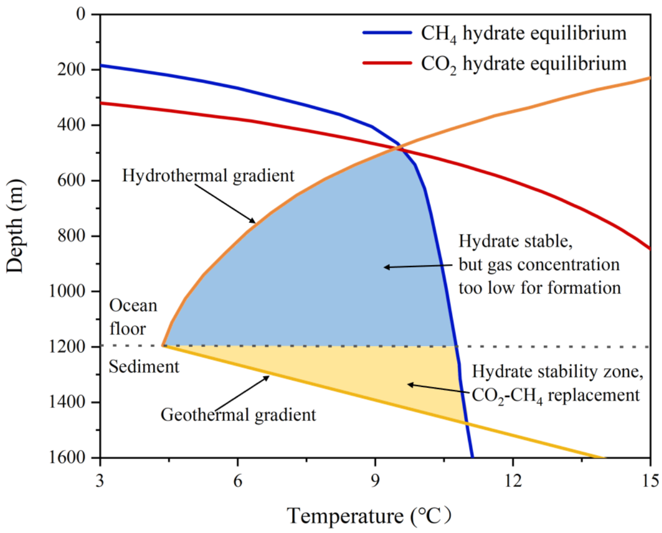

Figure 3. Phase equilibrium curve of methane and CO_2 [65]: The replacement reaction is influenced by the geothermal gradient. The blue and yellow parts enveloped by the curves are the hydrate stability zone, where hydrate can form in the sediments. However, due to the low concentration of gases in seawater, most of the hydrates are formed in the sediments, shown in the yellow part.

There are several factors that limit the practical application of the replacement and sequestration processes. Firstly, the replacement method is not universally applicable to all seabed reservoirs, as CO_2 replacement of CH_4 necessitates specific temperature and pressure conditions. If these conditions are not met, the replacement process cannot be effectively carried out. Additionally, during the extraction of other forms of combustible ice, the stability of CO_2 hydrate must be taken into account. Although CO_2 hydrate exhibits greater stability than combustible ice, it may decompose beyond particular temperature and pressure ranges [66]. Nevertheless, the replacement method possesses significant potential for delivering substantial environmental benefits, such as CO_2 sequestration, as well as economic advantages stemming from methane gas extraction. Importantly, the process does not interfere with the hydrate formation structure, ensuring seabed geomechanical stability throughout the procedure [65].

Future research directions for CO_2 replacement sequestration may concentrate on investigating the underlying replacement mechanism and determining strategies for enhancing replacement efficiency. Yahaya et al. [67] discovered that replacement efficiency is positively correlated with both temperature and pressure, with the effect of temperature being more pronounced than that of pressure under specific experimental conditions. Therefore, it is recommended to take appropriate measures to increase the replacement time and temperature. Mohammadi et al. [68] and Wang et al. [69] suggested the incorporation of catalysts to improve the replacement rate and the utilization of CO_2 emulsions in the CO_2-CH_4 replacement process to improve replacement efficiency. In addition, studies conducted by Pivnyak et al. [70] and Shin et al. [71] have demonstrated that the inclusion of an appropriate concentration of N_2 during the replacement process can accelerate the replacement rate. Through experimentation, Niu et al. [72] established that injecting a CO_2-N_2 mixture in the sequestration zone is a viable method for enhancing the efficiency of CO_2 sequestration. However, it is crucial to exercise control over the components of the injected mixture. Geng et al. [73] identified that electrostatic interaction plays a pivotal role in the replacement process and that optimizing the electrostatic interaction with H2O is an effective way to improve the replacement efficiency.

At present, the application of NGH replacement for CO_2 sequestration remains in the experimental stage, and the relevant technologies and sequestration methods are predominantly in the realm of theoretical exploration. Table 1 shows the methods to improve the efficiency of replacement. There is an urgent need for continued investigation and development in this area of research. Future research should focus on a more comprehensive understanding of the alternative mechanisms and structures of various seafloor sediments. This approach will help establish a sequestration mechanism suitable for different sediment types, thus laying a solid foundation for potential large-scale commercial applications in the future.

Table 1. The measures to improve the effectiveness of replacement.

Measures	Reference	Conclusion
temperature and pressure	Yahaya et al. [67]	The influence on the temperature is more significant than the replacement on pressure.
catalysts	Mohammadi et al. [68] and Wang et al. [69]	Catalysts or using CO_2 emulsion can improve the replacement rate.
adding N_2	Pivnyak et al. [70] and Shin et al. [71] and Niu et al. [72]	Appropriate concentration of N_2 could accelerate the replacement rate.
electrostatic interaction	Geng et al. [73]	Improving the electrostatic interaction with H2O is an effective way to improve the replacement efficiency.

4. Effects of CO_2 Marine Geological Sequestration on the Marine Environment

Although CO_2 marine geological sequestration offers promising potential, gas leakage during the process of CO_2 sequestration is inevitable, leading to environmental concerns such as ocean acidification, geological hazards, and enhanced greenhouse effects.

In marine geological sequestration, converting CO_2 into seabed sediment can create issues with unstable pore pressure, increasing hydrate formation temperature, and CO_2 leakage. These could lead to acidification of the sediment environment, causing chemical alterations that change the solubility or permeability of certain elements, releasing harmful metal ions that can damage marine ecosystems and organisms [74–76]. Additionally, during the process of substituting CO_2 for NGH, CH_4 leakage from pipeline transportation poses an even greater risk than CO_2, as the greenhouse effect of methane is significantly more severe. It is, therefore, essential to reduce this as much as possible.

Marine geological sequestration is a potential future solution for mitigating the accumulation of anthropogenic CO_2 in the atmosphere. However, during the implementation of marine geological sequestration, it is essential to detect and monitor the impact of stored CO_2 on the marine environment. Thus, comprehensive marine geological sequestration technology for CO_2 leakage detection and monitoring must be developed and established before commercial seabed sequestration can be implemented [77].

5. Conclusions and Future Perspectives

In summary, the advantages and constrains of the three marine geological sequestration technologies are shown in Table 2.

Table 2. Comparison of advantages and constrains of each sequestration technology.

Marine Geological Sequestration Technology	Advantages	Constrains	Gaps and Technical Barriers
Sequestration in shallow sediment	With abundant pore space and unconsolidated skeleton structure, the sequestration process does not need drilling	Permeability is reduced, causing the diffusion difficult to the far field	Complexity of early exploration work and the massive pressure of pipeline
Sequestration in sub-seabed aquifers	High sequestration security and reliability	Sequestration cost is high, pipeline pressure is too high	Complexity of early exploration work and the massive pressure of pipeline
CO_2-CH_4 replacement	It can not only store CO_2, but also extract CH_4 without disturbing formation stability.	Low replacement efficiency	Unclear replacement mechanisms and low replacement efficiency

Compared with terrestrial sequestration, marine geological sequestration has the characteristics of being far away from aquifers, stable high-temperature pressure, sealing, and perfect security, so it has greater potential. However, in terms of strengthening offshore oil, CO_2 marine geological sequestration technology still has many problems to solve:

1. Implementing CO_2 sequestration in shallow marine sediments is a challenge due to the complexity of early exploration work and the enormous pressure of the pipeline. At present, there are still shortcomings, such as unclear CH_4- CO_2 replacement mechanism and low replacement efficiency.
2. A significant number of existing studies have primarily focused on theoretical aspects, with a noticeable lack of concrete case studies and accurate data feedback. This limitation has emerged as a significant obstacle to advancing the research. Furthermore, even some well-versed individuals have a limited understanding of CO_2 sequestration. National policies, laws, and regulations regarding CO_2 marine geological sequestration are notably absent, stifling motivation for further study among both enterprises and individuals. As a result, the development of CO_2 marine geological sequestration technology still requires substantial advancement.
3. From an engineering perspective, the aggregate cost of CO_2 capture, transportation, and sequestration in CO_2 marine geological sequestration is markedly higher than that of geological sequestration. In the specific case of the transportation phase, marine pipelines demand significantly higher pressure and lower temperature conditions. This requires the use of more flexible pipe materials and, therefore, costs more. Challenges such as geological exploration in the marine environment, unique aspects of marine construction, trenching and backfilling in deep ocean high-pressure environments, and pipeline installation all lead to considerable cost implications. In addition, preliminary tasks such as deep drilling and seismic exploration, which are essential for offshore operations, are much more complex and costly than those performed on land.

While CO_2 marine geological sequestration still confronts numerous challenges, this technology undeniably represents the future direction of CO_2 sequestration. Bearing the mission of achieving carbon neutrality and peak carbon emissions in the world, CO_2 marine geological sequestration undoubtedly has a considerable journey ahead. To reach these goals, robust support and encouragement from the state and government are essential. The improvement of related laws and regulations can serve to motivate enterprises and individuals to study CO_2 marine geological sequestration, boost public awareness, and establish new experimental sites that provide tangible data feedback. In addition, research should prioritize strengthening CO_2 leakage monitoring mechanisms and continuously improve the accuracy and authenticity of various monitoring technologies. Meanwhile, a commitment to ensuring quality is essential to minimize the investment costs associated with these technologies. Only through the implementation of such comprehensive measures can we encourage continued collaboration between enterprises and individuals toward achieving the development goals of CO_2 marine geological sequestration.

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Abbreviations

NGH	natural gas hydrate
HBS	hydrate-bearing sediment
HCS	Hydrate-based CO_2 sequestration
NBZ	negative buoyancy zone
HFZ	hydrate forming zone

References

1. Leung, D.; Caramanna, G.; Maroto-Valer, M.M. An overview of current status of carbon dioxide capture and storage technologies. *Renew. Sustain. Energy Rev.* **2014**, *39*, 426–443. [CrossRef]
2. Metz, B.; Davidson, O.; De Coninck, H.C.; Loos, M.; Meyer, L. *The IPCC Special Report on Carbon Dioxide Capture and Storage (CCS)*; Cambridge University Press: Cambridge, UK, 2005; p. 481.
3. Zhao, Y.; Itakura, K.-I. A State-of-the-Art Review on Technology for Carbon Utilization and Storage. *Energies* **2023**, *16*, 3992. [CrossRef]
4. Inkeri, E.; Tynjälä, T. Modeling of CO_2 Capture with Water Bubble Column Reactor. *Energies* **2020**, *13*, 5793. [CrossRef]
5. Zeng, M.; Ouyang, S.; Zhang, Y.; Shi, H. CCS technology development in China: Status, problems and countermeasures—Based on SWOT analysis. *Renew. Sustain. Energy Rev.* **2014**, *39*, 604–616.
6. Jiang, K.; Ashworth, P.; Zhang, S.; Liang, X.; Sun, Y.; Angus, D. China's carbon capture, utilization and storage (CCUS) policy: A critical review. *Renew. Sustain. Energy Rev.* **2020**, *119*, 109601. [CrossRef]
7. Stevens, S.H.; Kuuskraa, V.A.; Gale, J.; Beecy, D. CO_2 Injection and Sequestration in Depleted Oil and Gas Fields and Deep Coal Seams: Worldwide Potential and Costs. *Environ. Geosci.* **2001**, *8*, 200–209. [CrossRef]
8. Rezaei, F.; Rezaei, A.; Jafari, S.; Hemmati-Sarapardeh, A.; Mohammadi, A.H.; Zendehboudi, S. On the Evaluation of Interfacial Tension (IFT) of CO_2–Paraffin System for Enhanced Oil Recovery Process: Comparison of Empirical Correlations, Soft Computing Approaches, and Parachor Model. *Energies* **2021**, *14*, 3045. [CrossRef]
9. Afzali, S.; Mohamadi-Baghmolaei, M.; Zendehboudi, S. Application of Gene Expression Programming (GEP) in Modeling Hydrocarbon Recovery in WAG Injection Process. *Energies* **2021**, *14*, 7131. [CrossRef]
10. Gale, J.; Freund, P. Coal-Bed Methane Enhancement with CO_2 Sequestration Worldwide Potential. *Environ. Geosci.* **2010**, *8*, 210–217. [CrossRef]
11. Fox, J.F.; Campbell, J.E.; Acton, P.M. Carbon Sequestration by Reforesting Legacy Grasslands on Coal Mining Sites. *Energies* **2020**, *13*, 6340. [CrossRef]
12. Kaplan, R.; Kopacz, M. Economic Conditions for Developing Hydrogen Production Based on Coal Gasification with Carbon Capture and Storage in Poland. *Energies* **2020**, *13*, 5074. [CrossRef]
13. Nordbotten, J.M.; Celia, M.A.; Bachu, S. Injection and Storage of Co: Analytical Solution for CO_2 Plume Evolution during InjectioN_2: Analytical Solution for CO_2 Plume Evolution during Injection in Deep Saline Aquifers: Analytical Solution for CO_2 Plume Evolution during Injection. *Transp. Porous Media* **2005**, *58*, 339–360. [CrossRef]
14. Shaffer, G. Long-term effectiveness and consequences of carbon dioxide sequestration. *Nat. Geosci.* **2010**, *3*, 464–467. [CrossRef]
15. Zhang, X.; Li, J.; Wu, Q.; Nan, J.; Jiao, L. Feasibility study on replacement of CH_4 gas from methane hydrate with CO_2 in frigid permafrost region. *Chem. Ind. Eng. Prog.* **2014**, *33*, 133–140.
16. Randolph, J.B.; Saar, M.O. Coupling carbon dioxide sequestration with geothermal energy capture in naturally permeable, porous geologic formations: Implications for CO_2 sequestration. *Energy Procedia* **2011**, *4*, 2206–2213. [CrossRef]

17. Aminu, M.D.; Nabavi, S.A.; Rochelle, C.A.; Manovic, V. A review of developments in carbon dioxide storage. *Appl. Energy* **2017**, *208*, 1389–1419. [CrossRef]
18. Bachu, S.; Bonijoly, D.; Bradshaw, J.; Burruss, R.; Mathiassen, O.M. CO_2 storage capacity estimation: Methodology and gaps. *Int. J. Greenh. Gas Control* **2007**, *1*, 430–443. [CrossRef]
19. Wang, J.G.; Ju, Y.; Gao, F.; Peng, Y.; Gao, Y. Effect of CO_2 sorption-induced anisotropic swelling on caprock sealing efficiency. *J. Clean. Prod.* **2015**, *103*, 685–695. [CrossRef]
20. Abdelrehim, N.; Cenci, S.; Corsini, L.; Dixon, J.; Jones, C.; Khanna, S.; Mathison, C.; Petersen, K.; Turley, C.; Whitmarsh, L. The Urgency of Climate Mitigation for COP27 and Beyond. In *UK Universities Climate Network Briefing*; 2022. Available online: https://www.researchgate.net/profile/Carol-Turley/publication/368709299_The_Urgency_of_Climate_Mitigation_for_COP27_and_Beyond_UK_Universities_Climate_Network_Briefing/links/63f62db00d98a97717ad4d76/The-Urgency-of-Climate-Mitigation-for-COP27-and-Beyond-UK-Universities-Climate-Network-Briefing.pdf (accessed on 1 June 2023).
21. Marchetti, C. On geoengineering and the carbon dioxide problem. *Clim. Chang.* **1976**, *1*, 59–68. [CrossRef]
22. Koide, H.; Shindo, Y.; Tazaki, Y.; Iijima, M.; Ito, K.; Kimura, N.; Omata, K. Deep sub-seabed disposal of CO_2—The most protective storage. *Energy Convers. Manag.* **1997**, *38*, S253–S258. [CrossRef]
23. Fujioka, Y.; Ozaki, M.; Takeuchi, K.; Shindo, Y.; Yanagisawa, Y.; Komiyama, H. Ocean CO_2 sequestration at the depths larger than 3700 m. *Energy Convers. Manag.* **1995**, *36*, 551–554. [CrossRef]
24. Haszeldine, R.S. Carbon capture and storage: How green can black be? *Science* **2009**, *325*, 1647–1652. [CrossRef] [PubMed]
25. Wang, J.; Yuan, Y.; Chen, J.; Zhang, W.; Zhang, J.; Liang, J.; Zhang, Y. Geological Conditions and Suitability Evaluation for CO_2 Geological Storage in Deep Saline Aquifers of the Beibu Gulf Basin (South China). *Energies* **2023**, *16*, 2360. [CrossRef]
26. Li, C.; Zhao, X.; Duan, W.; Wu, T.; Yao, Z.; Chen, G.; Li, G.; Peng, X. Strategic and geodynamic analyses of geo-sequestration of CO_2 in China offshore sedimentary basins. *Chin. J. Theor. Appl. Mech.* **2022**, *55*, 719–731.
27. Luo, J.; Xie, Y.; Hou, M.Z.; Xiong, Y.; Wu, X.; Lüddeke, C.T.; Huang, L. Advances in subsea carbon dioxide utilization and storage. *Energy Rev.* **2023**, *2*, 100016. [CrossRef]
28. House, K.Z.; Schrag, D.P.; Harvey, C.F.; Lackner, K.S. Permanent carbon dioxide storage in deep-sea sediments. *Proc. Natl. Acad. Sci. USA* **2006**, *103*, 12291–12295, Erratum in *Proc. Natl. Acad. Sci. USA* **2006**, *103*, 14255. [CrossRef]
29. Sun, D.; Englezos, P. Storage of CO_2 in a partially water saturated porous medium at gas hydrate formation conditions. *Int. J. Greenh. Gas Control* **2014**, *25*, 1–8. [CrossRef]
30. Li, X.C.; Yuan, W.; Bai, B. A review of numerical simulation methods for geomechanical problems induced by CO_2 geological storage. *Rock Soil Mech.* **2016**, *37*, 1762–1772.
31. Davis, E.E.; Becker, K. Observations of natural-state fluid pressures and temperatures in young oceanic crust and inferences regarding hydrothermal circulation. *Earth Planet. Sci. Lett.* **2002**, *204*, 231–248. [CrossRef]
32. Almenningen, S.; Gauteplass, J.; Fotland, P.; Aastveit, G.L.; Barth, T.; Ersland, G. Visualization of hydrate formation during CO_2 storage in water-saturated sandstone. *Int. J. Greenh. Gas Control* **2018**, *79*, 272–278. [CrossRef]
33. Gerami, T.S. CO_2 disposal as hydrate in ocean sediments. *J. Nat. Gas Sci. Eng.* **2012**, *8*, 139–149.
34. Qanbari, F.; Pooladi-Darvish, M.; Tabatabaie, S.H.; Gerami, S. Storage of CO_2 as hydrate beneath the ocean floor. In Proceedings of the 10th International Conference on Greenhouse Gas Control Technologies, Amsterdam, The Netherlands, 19–23 September 2010; pp. 3997–4004.
35. Beaudoin, G.; Ross, A. The BP OBS node experience: Deepening the reach of ocean bottom seismic. *Seg Tech. Program Expand. Abstr.* **2008**, 3713. [CrossRef]
36. Ray, A. First nodal OBS acquisition from the Thunder Horse Field in the deep water of the Gulf of Mexico. *Seg Tech. Program Expand. Abstr.* **2004**, *23*, 406.
37. Hassanpouryouzband, A.; Yang, J.; Tohidi, B.; Chuvilin, E.; Istomin, V.; Bukhanov, B.A.; Cheremisin, A. Insights into the CO_2 Capture by Flue Gas Hydrate Formation: Gas Composition Evolution in Systems Containing Gas Hydrates and Gas Mixtures at Stable Pressures. *ACS Sustain. Chem. Eng.* **2018**, *6*, 5732–5736. [CrossRef]
38. Yu, S.; Uchida, S. Geomechanical effects of carbon sequestration as CO_2 hydrates and CO_2-N_2 hydrates on host submarine sediments. *E3S Web Conf.* **2020**, *205*, 11003. [CrossRef]
39. Lee, S.; Liang, L.; Riestenberg, D.; West, O.R.; Tsouris, C.; Adams, E. CO_2 Hydrate Composite for Ocean Carbon Sequestration. *Environ. Sci. Technol.* **2003**, *37*, 3701–3708. [CrossRef]
40. Wu, P.; Li, Y. Microstructure Evolution of Hydrate-Bearing Sands During Thermal Dissociation and Ensued Impacts on the Mechanical and Seepage Characteristics. *J. Geophys. Res. Solid Earth* **2020**, *125*, e2019JB019103. [CrossRef]
41. Kalorazi, B.T. CO_2 hydrates could provide secondary safety factor in subsurface sequestration of CO_2. *Environ. Sci. Technol.* **2010**, *44*, 1509–1514.
42. Benson, S.M.; Dorchak, T.; Jacobs, G.; Ekmann, J.; Grahame, T. *Carbon Dioxide Reuse and Sequestration: The State of the Art Today*; Office of Scientific & Technical Information Technical Reports: Berkeley, CA, USA, 2000.
43. De Silva, P.N.K.; Ranjith, P.G. A study of methodologies for CO_2 storage capacity estimation of saline aquifers. *Fuel* **2012**, *93*, 13–27.
44. Metz, B.; Davidson, O.; Coninck, H.D.; Loos, M.; Meyer, L. *Carbon Dioxide Capture and Storage*; Intergovernmental Panel on Climate Change: Geneva, Switzerland, 2005.

45. Goldberg, D.S.; Takahashi, T.; Slagle, A.L. Carbon dioxide sequestration in deep-sea basalt. *Proc. Natl. Acad. Sci. USA* **2008**, *105*, 9920–9925. [CrossRef]
46. Rosenbauer, R.J.; Thomas, B.; Bischoff, J.L.; Palandri, J. Carbon sequestration via reaction with basaltic rocks: Geochemical modeling and experimental results. *Geochim. Cosmochim. Acta* **2012**, *89*, 116–133. [CrossRef]
47. Luhmann, A.J.; Tutolo, B.M.; Tan, C.; Moskowitz, B.M.; Saar, M.O.; Seyfried, W.E. Whole rock basalt alteration from CO_2-rich brine during flow-through experiments at 150 °C and 150 bar. *Chem. Geol.* **2017**, *453*, 92–110. [CrossRef]
48. Goldberg, D.S.; Slagle, A.L. A global assessment of deep-sea basalt sites for carbon sequestration. *Energy Procedia* **2009**, *1*, 3675–3682. [CrossRef]
49. Eccles, J.K.; Pratson, L. Global CO_2 storage potential of self-sealing marine sedimentary strata. *Geophys. Res. Lett.* **2012**, *39*. [CrossRef]
50. Furre, A.K.; Eiken, O. Dual sensor streamer technology used in Sleipner CO_2 injection monitoring. *Geophys. Prospect.* **2014**, *62*, 1075–1088. [CrossRef]
51. Baklid, A.; Korbol, R.; Owren, G. Sleipner vest CO_2 disposal, CO_2 injection into a shallow underground aquifer. In Proceedings of the SPE Annual Technical Conference and Exhibition, Denver, CO, USA, 6–9 October 1996.
52. Verdon, J.P.; Kendall, J.M.; Stork, A.L.; Chadwick, R.A.; White, D.J.; Bissell, R.C. Comparison of geomechanical deformation induced by megatonne-scale CO_2 storage at Sleipner, Weyburn, and In Salah. *Proc. Natl. Acad. Sci. USA* **2013**, *10*, E2762–E2771.
53. Widdicombe, S.; Dashfield, S.L.; McNeill, C.L.; Needham, H.R.; Beesley, A.H.; McEvoy, A.W.; Øxnevad, S.; Clarke, K.R.; Berge, J.A. Effects Of CO_2 Induced Seawater Acidification on Infaunal Diversity and Sediment Nutrient Fluxes. *Mar. Ecol. Prog. Ser.* **2009**, *379*, 59–75. [CrossRef]
54. Pegler, S.S.; Huppert, H.E.; Neufeld, J.A. Fluid Migration Between Confined Aquifers. *J. Fluid Mech.* **2014**, *757*, 330–353. [CrossRef]
55. Raknes, E.B.; Weibull, W.; Arntsen, B. Seismic Imaging of the Carbon Dioxide Gas Cloud at Sleipner Using 3D Elastic Time-lapse Full Waveform Inversion. *Int. J. Greenh. Gas Control.* **2015**, *42*, 26–45. [CrossRef]
56. Shahkarami, A.; Mohaghegh, S.D.; Gholami, V.; Haghighat, A.; Moreno, D.A. Modeling Pressure and Saturation Distribution In A Co2storage Project Using A Surrogate Reservoir Model (Srm). *Greenh. Gas Sci. Technol.* **2014**, *3*, 289–315. [CrossRef]
57. He, J.; Liang, Q.; Ma, Y.; Shi, Y.; Xia, Z. Geohazards types and their distribution characteristics in the natural gas hydrate area on the northern slope of the South China Sea. *Geol. China* **2018**, *45*, 15–28.
58. Brown, H.E.; Holbrook, W.S.; Hornbach, M.J.; Nealon, J. Slide structure and role of gas hydrate at the northern boundary of the Storegga Slide, offshore Norway. *Mar. Geol.* **2006**, *229*, 179–186. [CrossRef]
59. Santamarina, J.C.; Dai, S.; Terzariol, M.; Jang, J.; Waite, W.F.; Winters, W.J.; Nagao, J.; Yoneda, J.; Konno, Y.; Fujii, T. Hydro-bio-geomechanical properties of hydrate-bearing sediments from Nankai Trough. *Mar. Pet. Geol.* **2015**, *66*, 434–450. [CrossRef]
60. Ohgaki, K.; Takano, K.; Sangawa, H.; Matsubara, T.; Nakano, S. Methane Exploitation by Carbon Dioxide from Gas Hydrates—Phase Equilibria for CO_2-CH_4, Mixed Hydrate System. *J. Chem. Eng. Jpn.* **1996**, *29*, 478–483. [CrossRef]
61. Wilder, J.W.; Seshadri, K.; Smith, D.H. *Thermodynamics of the Sequestration of Carbon Dioxide in Methane Hydrates in Porous Media*; Abstracts of Papers of the American Chemical Society; American Chemical Society: Washington, DC, USA, 2002.
62. Kim, D.; Lee, H. Thermodynamic and Spectroscopic Analysis of Pure and Mixed Gas Hydrates Formed in Porous Media. *J. Health Sci.* **2003**, *7*, 7–15.
63. Yezdimer, E.M.; Cummings, P.T.; Chialvo, A.A. Determination of the Gibbs Free Energy of Gas Replacement in SI Clathrate Hydrates by Molecular Simulation. *J. Phys. Chem. A* **2002**, *106*, 7982–7987. [CrossRef]
64. Espinoza, D.N.; Santamarina, J.C. P-wave monitoring of hydrate-bearing sand during CH_4–CO_2 replacement. *Int. J. Greenh. Gas Control* **2011**, *5*, 1031–1038. [CrossRef]
65. Zhou, X.; Fan, S.; Liang, D.; Du, J. Determination of appropriate condition on replacing methane from hydrate with carbon dioxide. *Energy Convers. Manag.* **2008**, *49*, 2124–2129. [CrossRef]
66. Qi, Y.; Ota, M.; Hua, Z. Molecular dynamics simulation of replacement of CH_4 in hydrate with CO_2. *Energy Convers. Manag.* **2011**, *52*, 2682–2687. [CrossRef]
67. Yahaya, A.; Enyi, G.; Abbas, A.; Nasr, G. The influence of temperature and pressure on surface tension and bubble diameter of methane (CH_4) and Carbon dioxide (CO_2) in water. *J. Pet. Environ. Biotechnol.* **2017**, *8*, 46.
68. Mohammadi, A.H.; Eslamimanesh, A.; Richon, D. Semi-clathrate hydrate phase equilibrium measurements for the CO_2+H_2/CH_4+tetra-n-butylammonium bromide aqueous solution system. *Chem. Eng. Sci.* **2013**, *94*, 284–290. [CrossRef]
69. Wang, H.; Wu, Q.; Zhang, B. Influence of THF and THF/SDS on the Kinetics of CO_2 Hydrate Formation under Stirring. *Front. Energy Res.* **2021**, *9*, 633929. [CrossRef]
70. Pivnyak, G.; Bondarenko, V.; Kovalevs'Ka, I. *Technical and Geoinformational Systems in Mining: School of Underground Mining 2011*; CRC Press: Boca Raton, FL, USA, 2011.
71. Shin, K.; Park, Y.; Cha, M.; Park, K.P.; Huh, D.G.; Lee, J.; Kim, S.J.; Lee, H. Swapping Phenomena Occurring in Deep-Sea Gas Hydrates. *Energy Fuels* **2008**, *22*, 3160–3163. [CrossRef]
72. Niu, M.; Wu, G.; Yin, Z.; Sun, Y.; Chen, D. Effectiveness of CO_2-N_2 injection for synergistic CH_4 recovery and CO_2 sequestration at marine gas hydrates condition. *Chem. Eng. J.* **2021**, *420*, 129615. [CrossRef]
73. Geng, C.Y.; Wen, H.; Zhou, H. Molecular Simulation of the Potential of Methane Reoccupation during the Replacement of Methane Hydrate by CO_2. *J. Phys. Chem. A* **2009**, *113*, 5463. [CrossRef]

74. And, K.C.; Wickett, M.E. Ocean model predictions of chemistry changes from carbon dioxide emissions to the atmosphere and ocean. *J. Geophys. Res. Ocean.* **2005**, *110*, C09S04.
75. Dean, M.; Blackford, J.; Connelly, D.; Hines, R. Insights and guidance for offshore CO_2 storage monitoring based on the QICS, ETI MMV, and STEMM-CCS projects. *Int. J. Greenh. Gas Control* **2020**, *100*, 103120. [CrossRef]
76. Weber, V. Sub-seabed Carbon Dioxide Storage Regulation in the European Union—Environmental Law, the Law of the Sea and Liability. In Proceedings of the UKCCSC Winter School, Cambridge, UK, 9–12 January 2012.
77. Shitashima, K.; Maeda, Y.; Sakamoto, A. Detection and monitoring of leaked CO_2 through sediment, water column and atmosphere in a sub-seabed CCS experiment. *Int. J. Greenh. Gas Control* **2015**, *38*, 135–142. [CrossRef]