

Review

Emerging CO₂-Mineralization Technologies for Co-Utilization of Industrial Solid Waste and Carbon Resources in China

Junlin Meng ¹, Wenjie Liao ^{1,2,*} and Guoquan Zhang ³

¹ Institute of New Energy and Low-Carbon Technology, Sichuan University, Chengdu 610065, China; mjl0825@outlook.com

² Center of CCUS and CO₂ Mineralization and Utilization, Sichuan University, Chengdu 610065, China

³ School of Chemical Engineering, Sichuan University, Chengdu 610065, China; zhanggq@scu.edu.cn

* Correspondence: wenjieliao@scu.edu.cn or wenjieliao@outlook.com; Tel.: +86-28-6213-8375

Abstract: CO₂ mineralization (aka mineral carbonation) is a promising method for the chemical sequestration of CO₂ via reaction with oxides of alkaline or alkaline-earth metals to form carbonates. It has documented advantages over similar technological solutions to climate change. The huge amount of industrial solid waste, as a serious environmental issue confronted by China, can provide additional alkalinity sources for CO₂ mineralization. In this study, we present an overview of the latest advances in the emerging technologies of CO₂-mineralization via industrial solid waste in China, from the perspective of both theoretical and practical considerations. We summarize the types of industrial solid waste that are used (mainly coal fly ash, steel slag, phosphogypsum, and blast furnace slag) and the technological options available in the literature, with an emphasis on the discussion of the involved process-intensification methods and valuable chemicals produced. Furthermore, we illustrate the current status of pertinent policies, and research and development activities in China. Finally, we identify the current knowledge gaps, particularly in understanding the overall sustainability performance of these CO₂-mineralization technologies, and indicate that the technical, economic, and environmental challenges of promoting and commercializing these technologies for the co-utilization of industrial solid waste and carbon resources call for, amongst other things, more joint efforts by chemists, chemical engineers, and environmental scientists, and more feedback from the energy and industrial sectors.

Keywords: CO₂ mineralization; industrial solid waste; process intensification; sustainability assessment; climate change mitigation; circular economy



Citation: Meng, J.; Liao, W.; Zhang, G. Emerging CO₂-Mineralization Technologies for Co-Utilization of Industrial Solid Waste and Carbon Resources in China. *Minerals* **2021**, *11*, 274. <https://doi.org/10.3390/min11030274>

Academic Editor: Giovanni Ruggieri

Received: 31 January 2021

Accepted: 4 March 2021

Published: 7 March 2021

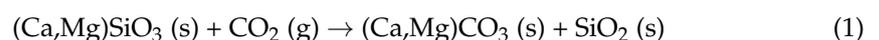
Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Carbon dioxide (CO₂) mineralization (aka mineral carbonation), first proposed by Seifritz [1], is an important part of the CO₂ capture, storage, and utilization (CCUS) technologies that are considered one of the effective ways to curb atmospheric greenhouse gas emissions for climate change mitigation [2]. It imitates the natural process of weathering silicate minerals, that is, CO₂ reacts with oxides of alkaline or alkaline-earth metals (e.g., calcium oxide (CaO) and magnesium oxide (MgO)) to form carbonates via the following reaction Formula (1) [3]:



The chemical properties of carbonates produced during the carbonation process are stable, resulting in almost permanent storage of CO₂ [4]. The reaction process is spontaneous exothermic [5] and thermodynamically favorable. At the same time, the wide range and huge reserves of alkalinity sources make mineral carbonation one of the most promising methods for CO₂ reduction.

A large number of natural minerals, such as serpentine [6,7], olivine [8], wollastonite [9], basalt [10], etc., react with CO₂ to produce stable carbonates. Industrial solid

waste (ISW) that is rich in CaO and MgO provides additional alkalinity sources for CO₂ mineralization, and its environmental impacts are mitigated via improved environmental stability after carbonation [11]. Typical ISW includes fly ash [12,13], steel slag [14,15], carbide slag [16], phosphogypsum [17,18], ore tailings [19], etc. At present, the use of ISW is more advantageous than natural minerals. ISW is more readily available from a wide range of sources and does not require separate mining, nor such energy-intensive and high-cost processing and pretreatment as natural minerals. ISW is cheaper, leading to lower costs of mineralization raw materials [20]; ISW has a higher alkalinity content, smaller particles, and higher reaction activity and rate. Furthermore, the application of CO₂ mineralization can also facilitate an industrial ecology approach in the ISW sector, recover valuable metals, and produce valuable chemicals; particularly, in the case of waste produced near a large number of CO₂ point sources, it is helpful for factories to adopt CO₂ mineralization technologies [21].

In the current era of the global response to the threat of climate change, the reduction of CO₂ emissions has become one key driving force for the construction of ecological civilization and sustainable development in China. As the world's largest energy consumer, China's primary energy consumption totaled 4.86 billion tons of standard coal equivalent in 2019, of which coal accounted for 57.7% [22]; fossil energy is expected to remain dominant in the near future [23]. Meanwhile, China's fossil CO₂ emissions reached over 10 Gt in 2019, accounting for 28% of the global fossil CO₂ emissions, and dominating the global trend [24]. In the long-term strategy of China's energy structure adjustment, CCUS is the key technological choice to realize the deep decarbonization and carbon neutrality of the fossil energy sector. With the accelerated process of industrialization, China's ISW has increased year by year, reaching 4.41 billion tons in 2019 [25]; and China has become one of the world's largest solid waste producing countries. With low-rates of treatment and utilization of ISW, large amounts of land resources have been occupied, increasing waste disposal costs and environmental burdens in China.

Technologies of CO₂ mineralization via ISW can fix CO₂, reduce and recycle ISW, and utilize ISW and waste CO₂ streams as secondary resources. They are an inevitable choice for China to achieve the dual goals of climate change mitigation and a circular economy and will have a significant contribution to global sustainable development. We thus present an overview of the latest advances in emerging technologies of CO₂-mineralization via ISW in China from the perspective of both theoretical and practical considerations, to make them understood by a broader international audience, as such an overview has not been reported so far.

2. Materials and Methods

This study mainly collected the literature of Chinese researchers to understand the current situation of CO₂ mineralization research in China. We used a two-step approach of literature review to search for the articles related to the topic. First, standardized search strings for CO₂ mineralization and ISW were employed in the databases CNKI, Wei Pu, Wan Fang, and Web of Science (Figure 1). Second, the scope of the results was further narrowed by reviewing the titles and abstracts and briefly browsing the contents following certain inclusion and exclusion criteria (Table 1). As a result, the literature search resulted in 55 articles in Chinese and 28 articles in English (see Appendix A for a list of English-language articles). We further explored advances in the research of CO₂ mineralization technologies in China according to the number of articles published, authors' affiliations, keywords, etc.



Figure 1. Strings used for a systematic literature search in the Web of Science database (accessed on 7 February 2021).

Table 1. Inclusion and exclusion criteria used for refining the literature search results.

Inclusive Criteria	Exclusion Criteria
Focusing on Chinese CO ₂ mineralization Is a peer-reviewed journal article	Is not related to industrial solid waste (ISW)

First of all, affiliations of the first author and the corresponding author of each article were counted to obtain Figure 1. Due to the novel research direction, the research on CO₂ mineralization via ISW in China is still in its infancy. Most institutions have only published one article in over 20 years, and the top six affiliations are limited to a small number of universities and research institutes, including Sichuan University, China University of Mining and Technology, Southwest University of Science and Technology, Chinese Academy of Sciences, Zhejiang University, and Huazhong University of Science and Technology. In addition, as CO₂ emissions have become the primary constraint on the development of the fossil energy sector, some enterprises, such as China Huaneng Group and Sinopec Group, have also begun to work on CO₂ mineralization technologies.

Figure 2 shows that since 2007, the number of pertinent articles has been increasing. Before 2012, the number of articles published each year was relatively small, less than two; after 2012, the number of articles published each year increased. The overall upward trend in the number of both Chinese-language and English-language articles indicates that more and more researchers have begun to pay attention to CO₂ mineralization technologies for the co-utilization of ISW and carbon resources. However, from the perspective of the overall numbers, the annual growth rate is relatively low, indicating that there are few researchers involved.

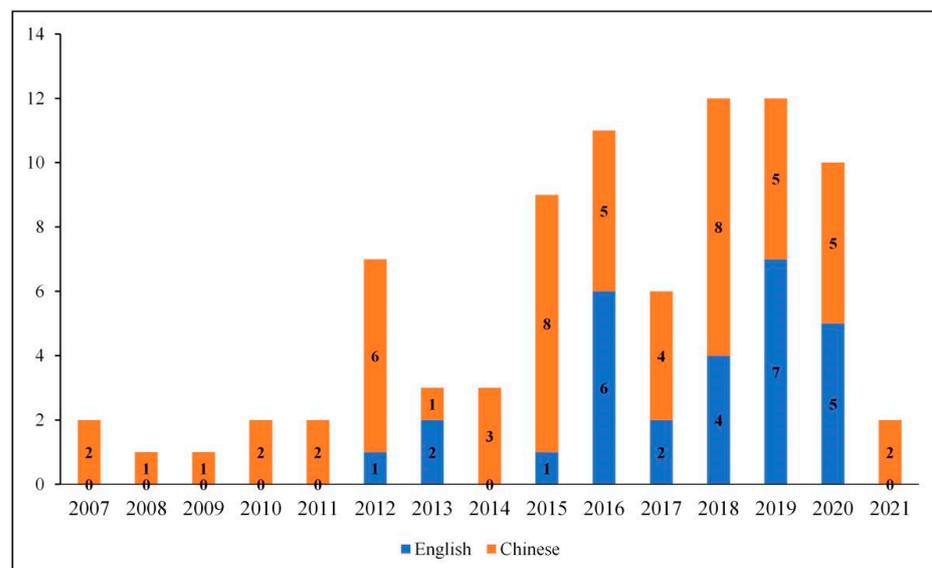


Figure 2. Total number of Chinese-language and English-language articles published each year from 2007 to 2021.

2.1. Large-Scale ISW in China

Based on the literature search results, we further discussed the research status and available technological options of CO₂ mineralization via ISW in China.

Figure 3 summarizes the lab-scale research on CO₂ mineralization via ISW in China. There are about a dozen types of ISW used in the lab-scale research, and the most reported ISW are fly ash, steel slag, and phosphogypsum. This can be explained by two reasons: first, power generation and steel production are the top CO₂ emitting sectors and deserve the most attention; second, fly ash, steel slag, and phosphogypsum are produced on a large scale, reused at low rates, and easy to obtain. About 45% of ISW was not treated or utilized in 2019 [26].

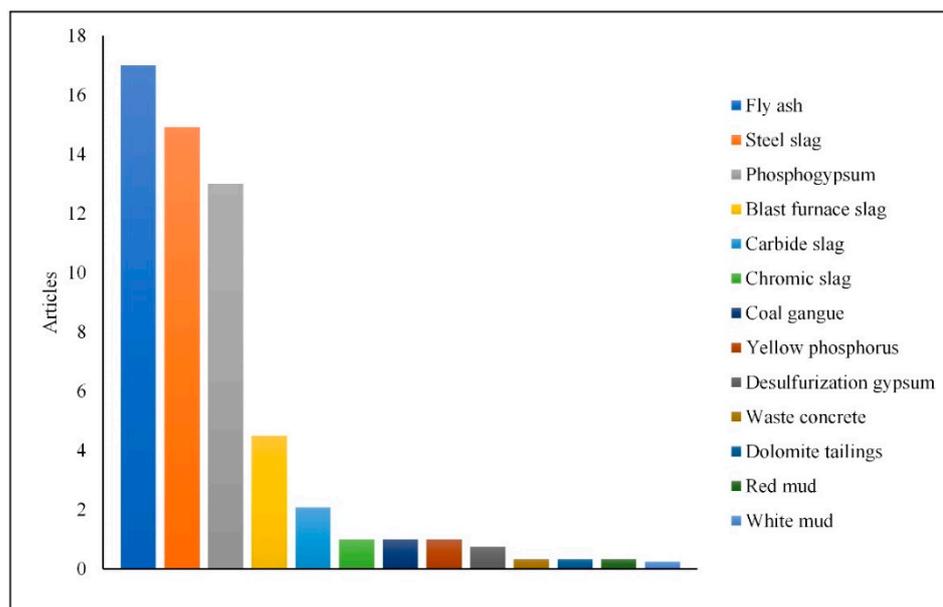


Figure 3. The type and article number of ISW involved in the lab-scale research of CO₂ mineralization in China (an article is regarded as 1 when it involves only one type of ISW; when an article involves N types of ISW, each type is regarded as 1/N article).

Fly ash is produced during industrial combustion, including municipal solid waste incineration ash and coal fly ash. Among them, coal fly ash is the small solid particles collected from post-combustion flue gas, mainly from the power and thermal producing sectors, and other sectors using coal-fired facilities such as chemical raw materials and chemicals manufacturing, non-ferrous metal smelting, and papermaking. As a large coal country, China's coal fly ash production has been high, totaling 540 million tons in 2019 [26]. It is believed that coal fly ash needs to be recycled rather than treated directly in landfills [27]. A lot of research has been done on the mineral carbonation of fly ash. The chemical compositions of coal vary with different sources and different combustion conditions [28]; although the contents of CaO and MgO are low, coal fly ash can still be used for CO₂ mineralization.

Steel slag is a steelmaking by-product, and the domestic steel slag production is about 10–15% of crude steel output in China [29]. China's crude steel output was 996 million tons, which accounted for 53.1% of global crude steel output in 2019 [30]. Assuming that the steel slag production is 12.5% of the crude steel production, China's steel slag production in 2019 was estimated as 125 million tons. Steel slag has a high alkalinity of CaO and MgO [31]. In addition, depending on ore compositions, steel slag may also contain vanadium, nickel, titanium, and other metal elements. Due to low utilization rates, a large number of steel slag deposits occupy land, and the heavy metal elements contained cause serious pollution to soil and groundwater. CO₂ mineralization via steel slag can not only capture CO₂

emitted by the steel plants to reduce CO₂ emissions, but also utilize steel slag and CO₂ to produce building materials [32].

Phosphogypsum (CaSO₄·2H₂O) is a waste residue formed in the production of phosphoric acid from phosphorus ore. As it contains a small amount of impurities, such as phosphorus and fluorine, it accumulates for a long period and is difficult to use effectively. China's phosphogypsum stock is over 600 million tons, with an annual output of 75 million tons, and less than 40% is comprehensively utilized. The environmental risks and pressures remain enormous. At present, the large-scale utilization of phosphogypsum is mainly concentrated in building materials [33] and the chemical industry [34].

Blast furnace slag is a meltable mixture that is composed of ore gangue, fuel ash, non-volatile components insolvent, and impurities that cannot enter the raw iron. According to the state-of-the-art technologies in China, 0.3–0.6 tons of blast furnace slag is produced per ton of iron smelting. Due to the different ore grades and smelting methods, the chemical composition of blast furnace slag in China is very complex, with a wide range of fluctuations; however, there are four main components, viz., CaO, MgO, silica, and alumina, accounting for about 95% of the total weight of blast furnace slag. Many methods have been put forward to utilize blast furnace slag effectively [35], including waste heat utilization, cement production, and other value-added applications.

Carbide slag is a type of ISW discharged from the hydrolysis of calcium carbide to acetylene, with the main component being calcium hydroxide. It is estimated that about 40 million tons of calcium carbide are produced annually in China [36]. The discharge of carbide slag in China is increasing every year, and mostly landfilled or discarded after initial disposal at the early stage, resulting in a comprehensive utilization rate lower than 20% [37]. With industrial development and technological progress, carbide slag has gradually become a raw material in construction and building, environmental protection, chemicals, and other fields.

The maximum mineralization ability of ISW depends on its alkalinity content and different operating parameters for the mineralization process [38]. In this study, it is assumed that all the Ca and Mg elements in ISW are used to fix CO₂ (i.e., mineralization rate of 100%). Table 2 shows that blast furnace slag, steel slag, phosphogypsum, and carbide slag have higher theoretical CO₂ fixation capacities and thus higher potentials for CO₂ reduction than coal fly ash. This is because while the annual production of coal fly ash is higher, its alkalinity content is lower than other types of ISW.

Table 2. Main raw materials for mineral carbonation, and their theoretical CO₂ fixation capacities in China.

Raw Materials	Alkalinity Content (%) ¹		Annual Production (million tons)	CO ₂ Fixation Efficiency (t CO ₂ /t slag)		Theoretical Fixation Capacity (million tons)	
	CaO	MgO		Low	High	Low	High
Coal fly ash	1.5–5.5	0.6–2.0	540	0.02	0.07	0.10	0.35
Steel slag	40–60	5–15	125	0.37	0.64	0.46	0.80
Phosphogypsum	25.54–42.87	0.1–0.16	75	0.20	0.34	0.15	0.25
Blast furnace slag	38–39	1–13	320	0.31	0.45	0.99	1.44
Carbide slag	65–71	0.22–1.68	40	0.51	0.58	0.21	0.23

¹ Data sources for alkalinity content: coal fly ash, carbide slag [39]; steel slag and blast furnace slag [40]; phosphogypsum [41].

2.2. Process Intensification

Current research on the process intensification of CO₂ mineralization in China mainly focuses on the selection of suitable operating conditions, extractants, pretreatment methods, and reactor replacement. In order to improve CO₂ absorption capacity, the operating parameters such as particle size, temperature, liquid–solid ratio, CO₂ concentration, and partial pressure, water content, and reaction time were optimized. In order to improve the reaction rate, the temperature and pressure can be increased. However, mineral carbonation is an exothermic reaction. Therefore, too high or too low a temperature has certain limitations

on the reaction, and an appropriate increase in the partial pressure of CO₂ can significantly improve the conversion rate. In order to improve the leaching efficiency of target metal elements, the selection of additives is very important. Experimental studies involve weak acids (e.g., acetic acid), strong acid, and weak base salts (e.g., ammonium chloride, ammonium sulfate ((NH₄)₂SO₄)), neutral salts (e.g., ammonium acetate), organic amines (e.g., monoethanolamine), and multiphase composite agents). Commonly used additives include sodium salt (e.g., sodium carbonate, sodium chloride, sodium bicarbonate), organic solvent tributyl phosphate, etc. Grinding, activation (e.g., chemical and steam activation), microwave irradiation, and removal of silica inert surfaces are used in the pretreatment to increase the reaction rate. Most studies usually modify ISW raw materials in different ways, such as hydration, salt addition, hydration calcination, and alkali washing, to further optimize the mineralization reaction conditions. Commonly used reaction equipment includes a batch reactor, recirculating fluidized bed, three-phase fluidized bed, etc. Some studies used ultrasound to improve the process efficiency or used a high gravity and carbonic anhydrase coupling technique to intensify the mineralization process.

At present, there are still problems, such as high material and energy consumption, and high process cost, in CO₂ mineralization and utilization technologies [42]. Therefore, it is necessary to: summarize the practical experience and theoretical laws underlying the lab-scale research on process intensification; continuously optimize the process; move on towards process upscaling and integration; and promote technology development and application.

2.3. Valuable Chemicals Produced

Products of CO₂ mineralization via ISW in China are generally calcium-based CO₂ adsorption materials (e.g., high-purity calcium carbonate (CaCO₃)) and mostly used as construction and building materials, such as artificial aggregate, slag-based concrete, bricks, plates, etc. Other reported chemicals include potash fertilizers, aluminum-rich products, metal oxides (e.g., titania, alumina), sodium bicarbonate, etc. Further efforts are needed to demonstrate the commercial application of these products.

3. Current Status of Pertinent Policies and Research and Development Activities

3.1. China's Policies of Carbon Capture, Utilization, and Storage

CO₂ capture, utilization, and storage (CCUS) technologies in China have a short history of less than two decades and are still in the early stages of research and development (R&D), so the corresponding standards, regulations, and legal documents are still relatively few. Li et al. (2016) [43] have provided an excellent overview of China's CCUS policies from 2006 to 2013. This study builds upon their work and focuses on the latest CCUS policies since 2013.

In 2013, the Ministry of Science and Technology of China issued the 12th Five-Year Special Plan for CCUS Technology Development, which mentioned that China had entered a pilot-scale stage in key technologies of CO₂ fixation using metallurgical slag. The National Development and Reform Commission of China issued the Guidance Directory for Key Products and Services for Strategic Emerging Industries, and the Notice on Promoting CCUS Test Demonstration, which clearly identified CCUS as a strategic emerging technology, and encouraged CCUS demonstration projects, respectively. The Ministry of Environmental Protection (now the Ministry of Ecology and Environment) of China issued the Notice on Strengthening Environmental Protection for CCUS Pilot Demonstration Projects, calling for enhanced environmental impact assessment and monitoring. In the same year, the China Technology Strategic Alliance for CCUS Technology Innovation was established; it has held five China CCUS Technology International Forums for far, which have built a platform for international exchange and cooperation, and been of great significance for promoting CCUS technological progress, achievement transformation, and industrial development. In 2014–2015, the government introduced a number of policies to encourage and promote CCUS demonstration projects. In 2015, the National

Development and Reform Commission of China and the People's Bank of China issued the Guidelines for Green Bond Issuance and the List of Green Bond Support Projects (2015), approving green bonds as a legal financial instrument for CCUS investment [44].

In 2016, the Ministry of Environmental Protection of China issued the Technical Guidelines for Environmental Risk Assessment of CCUS (Trial), which was the first technical guide and specification for CCUS environmental risks in China, and defined the procedure and recommended a qualitative matrix method for the risk assessment of CCUS projects. In the 13th Five-Year Plan for Controlling Greenhouse Gas Emissions, the 13th Five-Year National Plan for Economic and Social Development, and the 13th Five-Year National Plan for Science and Technology Innovation, the State Council of China began to promote the pilot demonstration of key CCUS technologies in the industrial sectors. The Energy Technology Revolution and Innovation Action Plan (2016–2030) emphasized the innovation of CCUS technologies, identified the large-scale utilization of CO₂ resources, including CO₂ mineralization and utilization, as a key field for technology R&D, and specified the necessity of realizing the efficient and comprehensive utilization of slag, reflecting the large amount of solid waste generated in the steel and chemical sectors. In January 2020, the Ministry of Ecology and Environment China issued China's first-of-a-kind special report on CCUS.

In September 2020, the Chinese President announced at the United Nations General Assembly that China would increase its contribution to tackling climate change in an effort for achieving a peak in CO₂ emissions by 2030 and achieving carbon neutrality by 2060. China has incorporated CCUS into its Nationally Determined Contributions. All these commitments to the international community will bring forth more policies related to CCUS, such as the Administrative Measures for Carbon Emission Trading (Trial) which will be implemented in February 2021, to speed up the construction of the carbon emissions trading market in China, and facilitate a carbon pricing system for industrial sectors to lower their costs in applying CO₂ mineralization via ISW compared to other CCUS technologies.

It can be seen that the Chinese government has attached great importance to the R&D of CCUS, paying increasing attention to CCUS at the national level, and providing continuous policy support for CCUS. However, China does not currently have a specific law for climate change mitigation, or even applicable to CCUS technologies and projects [44]. In order to achieve the goal of carbon neutrality by 2060, China needs breakthrough negative emission technologies, such as CCUS, and a large amount of investment, as well as stronger policy measures. Therefore, China should formulate specific CCUS action plans suitable for the whole country or localities as soon as possible.

3.2. Demonstration Projects of CO₂ Mineralization Via ISW in China

The scaling up of tests and demonstrations is the only way towards the commercial application of technologies of CO₂ mineralization via ISW, through which the overall feasibility and potential for climate change mitigation and circular economy of CCUS technologies can be further explored. At present, a few CO₂ mineralization and utilization projects in China have entered the demonstration phase. They are cooperative projects between universities/research institutes and enterprises, with funding mainly from the Ministry of Science and Technology of China, and supplemented by the enterprises. Table 3 summarizes the projects of CO₂ mineralization via ISW demonstrated in China.

A pilot project for direct CO₂ mineralization via phosphogypsum from exhaust gas (100 Nm³h⁻¹) was completed by Sinopec Group and Sichuan University [42]. Phosphogypsum was used as the raw material, ammonia was directly absorbed by CO₂ from flue gas, and the absorption solution reacted with phosphogypsum for mineralization. The process can be expressed in the following formula:



In this process, flue gas was cooled with circulating water to a temperature of 50 °C and then entered the absorption tower. The CO₂ in the flue gas was absorbed by the

ammonia-rich solution, and converted to ammonium bicarbonate, and the purified flue gas CO₂ concentration was reduced from 15% to 4.5%. The purified gas then was scrubbed with acidic phosphogypsum slurry in acid pickling to reduce the absorbed trace ammonia residue from the gas phase, so that the ammonia concentration of exhaust gas was controlled to less than $1.0 \times 10^{-7} \mu\text{mol}\cdot\text{mol}^{-1}$. The CO₂-rich slurry was then pumped into a three-phase reactor, where it was further reacted with fresh phosphogypsum to form CaCO₃. The CaCO₃ was filtered, washed, and then dried at 250 °C to obtain the final product. Meanwhile, the (NH₄)₂SO₄ in the solution was crystallized and separated as a fertilizer product (see the process flow diagram in Figure 4). The final product was CaCO₃ and nitrogen fertilizer, with a conversion rate exceeding 92% and a CO₂ capture rate reaching 75%.

Table 3. Demonstration projects of CO₂ mineralization and utilization in China.

Cooperative Units	Raw Material	Source of CO ₂	Year	Products
Sinopec Group and Sichuan University	Phosphogypsum	Natural gas purification plant	2013	CaCO ₃ , (NH ₄) ₂ SO ₄
Sinochem Fuling Chongqing Chemical Industry Co., Ltd. and Chinese Academy of Sciences	Phosphogypsum	Ammonia synthesis plant	2017	CaCO ₃ , (NH ₄) ₂ SO ₄
Yuanchu Technology Corp. and Tsinghua University	Silicate ore, construction solid waste	Cement plant	2018	Light-weight CaCO ₃ , Silica
Henan Qiangnai New Materials Co., Ltd. and Zhejiang University	Steel slag, fly ash	Chemical plant	2020	Concrete brick

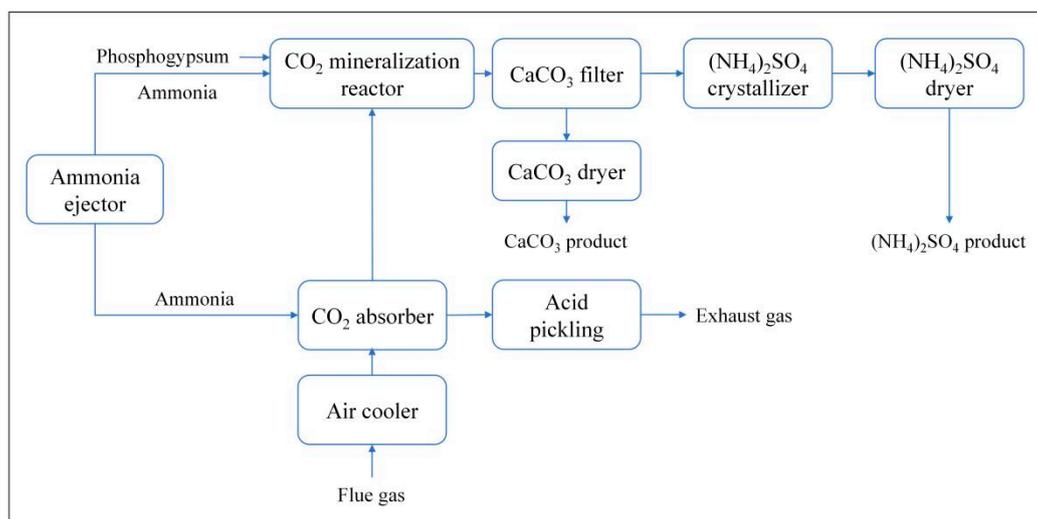


Figure 4. Process flow of CO₂ mineralization via phosphogypsum developed by Sinopec and Sichuan University [42].

Sinochem Chongqing Fuling Chemical Co., Ltd., in cooperation with the Chinese Academy of Sciences, established a demonstration plant with a mineralization capacity of 0.1 million tons of high-concentration phosphogypsum per year and achieved stable operation. The project enhanced the mineralization of CO₂ by absorbing high-concentration CO₂ from the ammonia synthesis process and using ammonia medium, and the calcium sulfate in phosphogypsum was converted into CaCO₃ and (NH₄)₂SO₄ (see the process flow diagram in Figure 5). The final products were (NH₄)₂SO₄ fertilizer and light CaCO₃.

The CaCO_3 produced had a purity of more than 99%, whiteness higher than 92%, and average particle size of 6.2 μm , and had a high added value [45]. Meanwhile, the carbonation conversion rate of phosphogypsum was above 97%, and the utilization rate of CO_2 was above 95%.

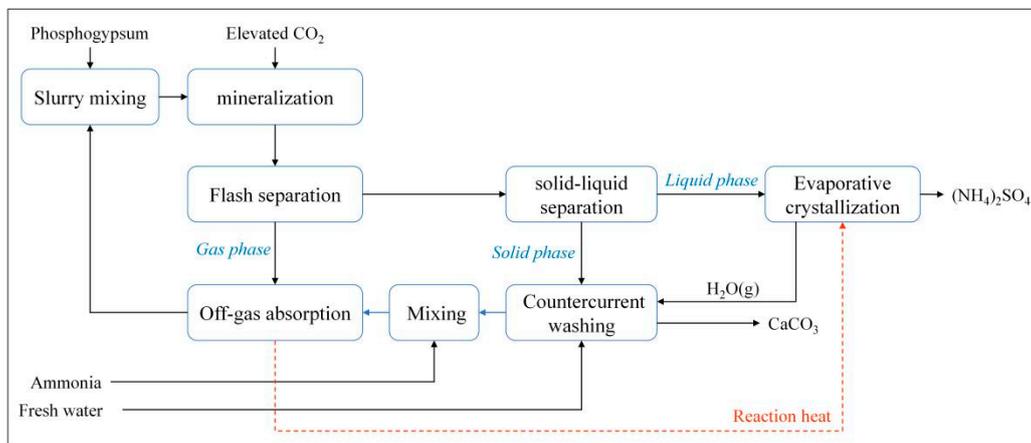


Figure 5. Process flow of high-concentration CO_2 mineralization via phosphogypsum developed by Sinochem and the Chinese Academy of Sciences [45].

Yuanchu Technology Corp. cooperated with Tsinghua University to build a CO_2 capture and utilization demonstration project based on chemical looping and mineralization via silicate ore and building solid waste. In this project, calcium-containing silicates and building solid waste were chlorinated, and the obtained calcium chloride was mixed with ammonia water and CO_2 ; a carbonation reaction was performed to convert CO_2 into CaCO_3 , and the generated ammonium chloride solution was recovered. The ammonium chloride solution, after being concentrated or hydrogen chloride being generated from a decomposition reaction of the ammonium chloride solution, was directly used to chlorinate the calcium-containing silicate. The designed capacity was 1000 tons of flue-gas CO_2 from the cement plant per year, with a mineralization rate of CO_2 over 90%, and a net capture rate of CO_2 over 50%. Light CaCO_3 and silica were produced. The enterprise has recently established another project to demonstrate similar technology at a coal-fired power plant.

Mineral carbonation curing technology is based on the carbonation reaction between the concrete material and CO_2 to achieve CO_2 storage, and improve the mechanical strength of concrete products. Henan Qiangnai New Materials Co., Ltd. and Zhejiang University jointly ran an industrial test of CO_2 deep mineral carbonation curing. Before the demonstration, a study of CO_2 curing of aerated concrete, based on three typical industrial wastes (fly ash, blast furnace slag, and red mud), was carried out, focusing on the effects of different curing times, pressures, and water-to-solid ratios on the CO_2 uptake and compressive strength [46]. The demonstration project established a new CO_2 curing system by reforming a set of traditional steam curing systems. Compared with the traditional steam curing process, this project did not need a high-temperature heat source and could achieve 10,000 tons of CO_2 storage and produce 100 million MU15 standard lightweight solid concrete bricks per year.

4. Current Knowledge Gaps

4.1. The Importance of Assessment of CO_2 Mineralization Technologies

China should learn from developed countries that started the research of CO_2 mineralization and other CCUS technologies earlier, in terms of technology development, engineering management, policies and regulations, and discipline development. In particular, target technology assessment is needed. In order to promote and commercialize technologies of CO_2 mineralization via ISW and explore their function and potential in achieving the multiple socioeconomic and environmental goals of circular economy and cli-

mate change mitigation, amongst others, it is necessary to assess and compare the maturity level and feasibility of different CO₂-mineralization technology options, and to identify the difficulties, obstacles, and requirements for technology development.

Technology assessment at the early stage of CO₂-mineralization technologies brings a large scope for improving their sustainability performance. For instance, if the market volume and average sustainability performance of the mineralization products for co-utilizing ISW and CO₂ resources are not systematically investigated and estimated, it will directly affect the motivation of enterprises to develop CO₂-mineralization technologies and affect the planning and layout of their value chains and the involved sectors. Life cycle thinking-based methods, such as life cycle assessment (LCA), life cycle costing, and life cycle sustainability assessment, are very relevant, as they cover the multiple inputs and outputs of CO₂ flows, multiple value-chain processes, and the multiple socioeconomic and environmental functions and impacts of the CO₂-mineralization technology systems. As technology performance changes with technology development, the sustainability assessment of a CO₂-mineralization technology should be conducted in a continuous iterative way as the technology develops through different levels of maturity, and even on reaching materiality.

4.2. Understanding of the Sustainability of CO₂ Mineralization Technologies

Technologies of CO₂ mineralization via ISW and other CCUS technologies alike involve a complex industrial chain. Before a large-scale deployment, the overall feasibility and sustainability of a technological option should be demonstrated. Researchers need to carefully evaluate the current status and operation of the project, including the technical feasibility, economic feasibility, environmental impacts, and risks, which provide corresponding suggestions for, and solutions to, the demonstration and industrialization of CO₂ mineralization projects in China.

4.2.1. Technical Feasibility

From the literature survey, we found that most of the articles focused on lab-scale research studying the corresponding reaction conditions for intensifying ISW carbonation, rather than the use and end-of-life treatment of mineralization products. Technologies of CO₂ mineralization via ISW are mostly in the experimental stage, only a few universities, research institutes, and enterprises have reached the pilot demonstration stage. This is also in line with the results of China's CCUS Technology Development Roadmap issued by the Ministry of Science of Technology [47]. As shown in Figure 6, CO₂ mineralization and utilization technologies were still at the stage of theoretical research before 2011, and experimental research began around 2016. At present, they are at the stage of small-scale demonstration (i.e., technology readiness level (TRL): 5–6), and large-scale industrial demonstrations have not been carried out.

Technologies of CO₂ mineralization are highly process integrated and emerging. It is thus necessary to promote the smooth development of all aspects in an orderly manner for technology selection. Especially in the process of the various pilot and demonstration projects, attention should be paid to the uncertainty of technology development. With further efforts by universities and research institutes and large-scale demonstration of enterprises, future innovations and breakthroughs will be made in technological parameters. As the technology learning effect comes into play, technology improvements will have a significant positive impact on the investment value and timing of CO₂ mineralization and utilization projects, facilitating the arrival of investment opportunities [48]. Similarly, a clear technology roadmap will help to understand the technological barriers at different stages and identify priorities for the R&D of CO₂ mineralization technologies [43].

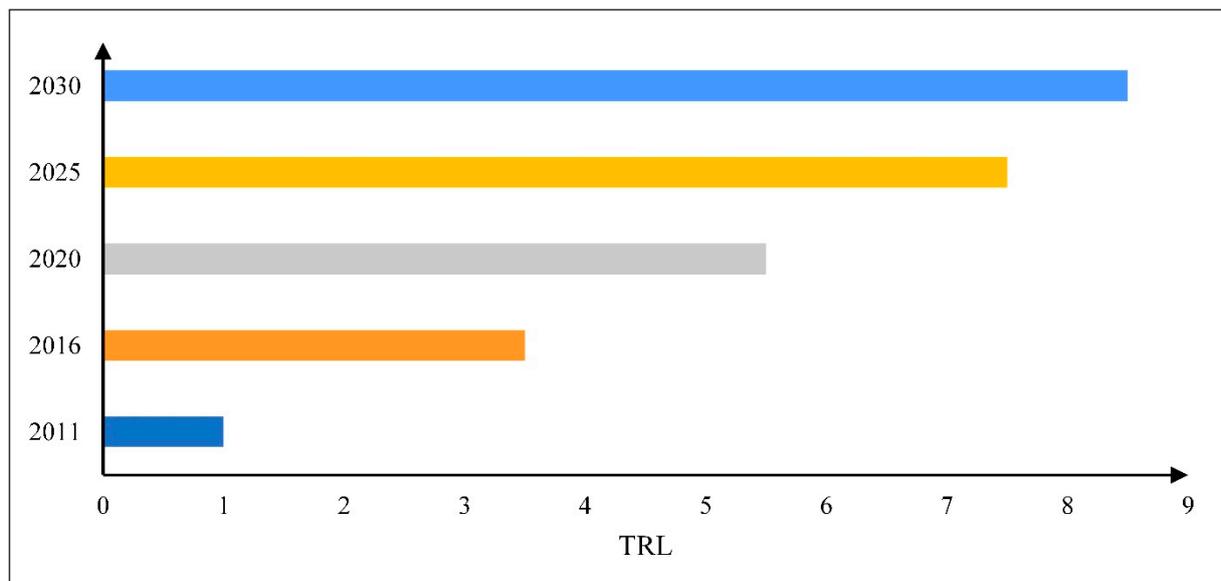


Figure 6. Maturity of CO₂ mineralization and utilization technologies in China.

4.2.2. Economic Feasibility

While projects of CO₂ mineralization via ISW bear high investment costs, there is still much room for improvement. To develop a circular economy, a large amount of ISW needs to be utilized comprehensively to achieve a balance of production and consumption. The economic feasibility of the projects should be assessed. Economic assessment of demonstration projects, such as in the steel, cement, coal chemical, and petrochemical industries, helps to quantify the product output, costs, and benefits of different sectors [49]. More attention should be paid to a project's whole life cycle cost. Since the cost of projects of CO₂ mineralization via ISW will be affected by many factors, not only the different prices of resources (including land, water, etc.), energy, and manpower, but also various product life-cycle processes, such as energy and material input production, CO₂ capture, pretreatment and transport, mineralization conversion, product use, and product end-of-life treatment. It is also important to consider the cost of the entire project life-cycle stages, such as storage potential assessment, design, construction, production and operation, monitoring, risk control, and decommissioning. The overall market volume of mineralization products should also be investigated. This will help to select the best integration of processes with the most economic profitability and lowest cost.

4.2.3. Environment Impacts and Risks

The environmental impacts of CO₂ mineralization technologies and projects are better assessed from a perspective of life cycle thinking. The application of LCA has changed the approach of environmental impact assessment, which has been limited to routine stages, such as production and processing, and has provided a broader perspective by integrating the product life cycle. LCA-based environmental impact assessment helps enterprises manage the environmental impacts of their entire product supply chain, thus designing and developing more environmentally friendly products. It can also be used to balance the energy and environmental impacts of CO₂ mineralization technologies considering the energy penalty caused by process intensification. Therefore, the environmental impacts associated with electricity and heat production, which are determined by the regional energy supply structure, should be considered. In the assessment of net CO₂ emissions, which is of high relevance to CO₂ mineralization via ISW as a technological solution for climate change mitigation, we should also consider the CO₂ emissions caused by raw material production and CO₂ credits by the avoidance of ISW treatment and marginal production of mineralization products. In this way, we can fully quantify the CO₂ emissions of technologies of

CO₂ mineralization via ISW, and determine a basis for measuring their China Certified Emission Reduction (CCER) in the carbon trading market. At present, CCER's accounting only considers the amount of CO₂ fixed in mineralization, direct emissions, and indirect emissions caused by energy production. It is recommended that CO₂ emissions within the scope of other life cycle processes be considered in the future carbon trading system.

The environmental risks in the life cycle of CO₂ mineralization projects should be assessed. Attention should be paid to the risks to human safety and the environment due to the leakage of CO₂ and other substances during construction, operation (particularly the capture and mineralization conversion of CO₂) [50], and decommissioning of the project. The results of the environmental impact and risk assessment should thus be used as one of the important screening indicators for the application, certification, and issuance of CO₂ mineralization projects.

4.3. Cooperation between Different Stakeholders

Technologies and projects of CO₂ mineralization via ISW involve multiple stakeholders including governments, enterprises and industries, research institutes and universities, the public, and individuals. Without the establishment of effective communication and cooperation mechanisms and business models, it will be difficult to achieve a good connection between these stakeholders, thus affecting the R&D, demonstration, and promotion of CO₂ mineralization technologies.

Multiple government departments are involved in policymaking for CO₂ mineralization technologies and projects. They have different functions, such as regulation formulation, land planning, and environmental protection, and cross-department coordination should be strengthened. They play a leading role in subsidizing demonstration projects at the early stages, which will facilitate the long-term deployment and operation of these projects [51], and in promoting enterprise technology innovation through market mechanisms, such as carbon emission trading. Mutual understanding with research institutes will also help to make more science-based policies and influence their effectiveness [52]. Enterprises are the implementers and managers, and research institutes play a supporting role, in the R&D and demonstration of CO₂ mineralization technologies. In order to get more accurate key technological information, and the correct explanation and interpretation of assessment results, more joint efforts by chemists, chemical engineers, and environmental scientists, and more feedback from the energy and industrial sectors are needed. In the current context, it also requires the long-term cooperation between enterprises and research institutes to generate more demonstration projects and explore more feasible climate change mitigation schemes coupled with CO₂ mineralization via ISW. Government departments, enterprises, and research institutes should share and crosscheck information to ensure a reliable basis for decision-making. The public's attitude is also very important. Other stakeholders should take the initiative to promote relevant knowledge to the public and ensure that some of the project's safety and environmental information is disclosed to avoid public opposition [53].

In addition, the cooperation on CO₂ mineralization technologies between China and the international community should be strengthened. The broad development of international cooperation provides channels for technology transfer and sharing and the establishment of cross-border markets. Through full participation in international cooperation and competition, technology R&D, demonstration, and even commercialization can be accelerated by introducing international resources to local conditions.

5. Conclusions

The technologies of CO₂ mineralization via ISW are promising to help achieve the dual goals of climate change mitigation and a circular economy in China. In this study, we present an overview of the latest advances in the emerging technologies of CO₂ mineralization via ISW in China, from the perspective of both theoretical and practical considerations. The main mineralization raw materials reported in the literature are coal fly

ash, steel slag, phosphogypsum, and blast furnace slag. The related research, with a focus on process intensification, has made great progress. However, the technologies are still in their early stages of development; the research mainly stays at the lab-scale, with a few demonstration projects. In order to promote the R&D and application of technologies of CO₂ mineralization via ISW, life cycle thinking-based methods are needed to improve the understanding of the overall feasibility and sustainability of these technologies, and more joint efforts by chemists, chemical engineers, and environmental scientists and more feedback from the energy and industrial sectors, amongst others, are needed to strengthen the cooperation between the different stakeholders of these CO₂-mineralisation technologies.

Author Contributions: Investigation, Methodology, Writing—original draft, J.M.; Conceptualization, Supervision, Writing—review & editing, W.L.; Investigation, Supervision, G.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research received support from the National Key Projects for Fundamental Research and Development of China (2016YFB0600904).

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

List of English-language articles on CO₂ mineralization via ISW in China
(in alphabetical order of the first author's last name)

1. Cao, W.; Yang, Q. The properties of the carbonated brick made of steel slag-slaked lime mixture.
2. Chen, Q.; Ding, W.; Sun, H.; Peng, T. Mineral carbonation of yellow phosphorus slag and characterization of carbonated product.
3. Ding, W.; Chen, Q.; Sun, H.; Peng, T. Modified mineral carbonation of phosphogypsum for CO₂ sequestration.
4. Gan, Z.; Cui, Z.; Yue, H.; Tang, S.; Liu, C.; Li, C.; Liang, B.; Xie, H. An efficient methodology for utilization of K-feldspar and phosphogypsum with reduced energy consumption and CO₂ emissions.
5. Gao, J.; Li, C.; Liu, W.; Hu, J.; Wang, L.; Liu, Q.; Liang, B.; Yue, H.; Zhang, G.; Luo, D.; et al. Process simulation and energy integration in the mineral carbonation of blast furnace slag.
6. Hu, J.; Liu, W.; Wang, L.; Liu, Q.; Chen, F.; Yue, H.; Liang, B.; Lu, L.; Wang, Y.; Zhang, G.; et al. Indirect mineral carbonation of blast furnace slag with (NH₄)₂SO₄ as a recyclable extractant.
7. Ji, L.; Yu, H.; Wang, X.; Grigore, M.; French, D.; Gozukara, Y.; Yu, J.; Zeng, M. CO₂ sequestration by direct mineralisation using fly ash from Chinese Shenfu coal.
8. Ji, L.; Yu, H.; Yu, B.; Jiang, K.; Grigore, M.; Wang, X.; Zhao, S.; Li, K. Integrated absorption–mineralisation for energy-efficient CO₂ sequestration: Reaction mechanism and feasibility of using fly ash as a feedstock.
9. Ji, L.; Yu, H.; Zhang, R.; French, D.; Grigore, M.; Yu, B.; Wang, X.; Yu, J.; Zhao, S. Effects of fly ash properties on carbonation efficiency in CO₂ mineralisation.
10. Jiang, J.; Tian, S.; Zhang, C. Influence of SO₂ in incineration flue gas on the sequestration of CO₂ by municipal solid waste incinerator fly ash.
11. Liu, W.; Su, S.; Xu, K.; Chen, Q.; Xu, J.; Sun, Z.; Wang, Y.; Hu, S.; Wang, X.; Xue, Y.; et al. CO₂ sequestration by direct gas-solid carbonation of fly ash with steam addition.
12. Luo, C.; Wu, K.; Yue, H.; Liu, Y.; Zhu, Y.; Jiang, W.; Lu, H.; Liang, B. DBU-based CO₂ absorption–mineralization system: Reaction process, feasibility and process intensification.
13. Ni, P.; Xiong, Z.; Tian, C.; Li, H.; Zhao, Y.; Zhang, J.; Zheng, C. Influence of carbonation under oxy-fuel combustion flue gas on the leachability of heavy metals in MSWI fly ash.

14. Shangguan, W.; Song, J.; Yue, H.; Tang, S.; Liu, C.; Li, C.; Liang, B.; Xie, H. An efficient milling-assisted technology for K-feldspar processing, industrial waste treatment and CO₂ mineralization.
15. Shen, W.; Liu, Y.; Wu, M.; Zhang, D.; Du, X.; Zhao, D.; Xu, G.; Zhang, B.; Xiong, X. Ecological carbonated steel slag pervious concrete prepared as a key material of sponge city.
16. Tan, W.; Gu, S.; Xia, W.; Li, Y.; Zhang, Z. Feature changes of mercury during the carbonation of FGD gypsum from different sources.
17. Tian, T.; Yan, Y.; Hu, Z.; Xu, Y.; Chen, Y.; Shi, J. Utilization of original phosphogypsum for the preparation of foam concrete.
18. Wang, L.; Chen, Q.; Jamro, I.A.; Li, R.; Li, Y.; Li, S.; Luan, J. Geochemical modeling and assessment of leaching from carbonated municipal solid waste incinerator (MSWI) fly ash.
19. Wang, L.; Liu, W.; Hu, J.; Liu, Q.; Yue, H.; Liang, B.; Zhang, G.; Luo, D.; Xie, H.; Li, C. Indirect mineral carbonation of titanium-bearing blast furnace slag coupled with recovery of TiO₂ and Al₂O₃.
20. Wang, P.; Mao, X.; Chen, S.-E. CO₂ sequestration characteristics in the cementitious material based on gangue backfilling mining method.
21. Xie, H.; Tang, L.; Wang, Y.; Liu, T.; Hou, Z.; Wang, J.; Wang, T.; Jiang, W.; Were, P. Feedstocks study on CO₂ mineralization technology.
22. Xiong, Y.; Aldahri, T.; Liu, W.; Chu, G.; Zhang, G.; Luo, D.; Yue, H.; Liang, B.; Li, C. Simultaneous preparation of TiO₂ and ammonium alum, and microporous SiO₂ during the mineral carbonation of titanium-bearing blast furnace slag.
23. Yi, H.; Xu, G.; Cheng, H.; Wang, J.; Wan, Y.; Chen, H. An overview of utilization of steel slag.
24. Zhang, H.; Dong, L.; Li, H.; Fujita, T.; Ohnishi, S.; Tang, Q. Analysis of low-carbon industrial symbiosis technology for carbon mitigation in a Chinese iron/steel industrial park.
25. Zhao, Q.; Liu, C.; Gao, T.; Gao, L.; Saxen, H.; Zevenhoven, R. Remediation of stainless steel slag with MnO for CO₂ mineralization.
26. Zhao, Q.; Liu, K.; Sun, L.; Liu, C.; Jiang, M.; Saxen, H.; Zevenhoven, R. Towards carbon sequestration using stainless steel slag via phase modification and co-extraction of calcium and magnesium.
27. Chen, Q.; Ding, W.; Sun, H.; Peng, T.; Ma, G. Utilization of Phosphogypsum to Prepare High-Purity CaCO₃ in the NH₄Cl–NH₄OH–CO₂ System.
28. Chen, Q.J.; Ding, W.J.; Sun, H.J.; Peng, T.J.; Ma, G.H. Indirect mineral carbonation of phosphogypsum for CO₂ sequestration.

References

1. Seifritz, W. CO₂ disposal by means of silicates. *Nature* **1990**, *345*, 486. [[CrossRef](#)]
2. Intergovernmental Panel on Climate Change (IPCC). *Special Report on Carbon Dioxide Capture and Storage*; Cambridge University Press: Cambridge, UK, 2005; ISBN 92-9169-1190-4.
3. Romanov, V.; Soong, Y.; Carney, C.; Rush, G.E.; Nielsen, B.; O'Connor, W. Mineralization of Carbon Dioxide: A Literature Review. *ChemBioeng. Rev.* **2015**, *2*, 231–256. [[CrossRef](#)]
4. Lackner, K.S.; Wendt, C.H.; Butt, D.P.; Joyce, E.L.; Sharp, D.H. Carbon dioxide disposal in carbonate minerals. *Energy* **1995**, *20*, 1153–1170. [[CrossRef](#)]
5. Moazzem, S.; Rasul, M.G.; Khan, M.M.K. Energy recovery opportunities from mineral carbonation process in coal fired power plant. *Appl. Therm. Eng.* **2013**, *51*, 281–291. [[CrossRef](#)]
6. Teir, S.; Kuusik, R.; Fogelholm, C.-J.; Zevenhoven, R. Production of magnesium carbonates from serpentinite for long-term storage of CO₂. *Int. J. Miner. Process.* **2007**, *85*, 1–15. [[CrossRef](#)]
7. Nduagu, E.; Fagerlund, J.; Zevenhoven, R. Contribution of iron to the energetics of CO₂ sequestration in Mg–silicates-based rock. *Energy Convers. Manag.* **2012**, *55*, 178–186. [[CrossRef](#)]
8. Kremer, D.; Wotruba, H. Separation of Products from Mineral Sequestration of CO₂ with Primary and Secondary Raw Materials. *Minerals* **2020**, *10*, 1098. [[CrossRef](#)]

9. Tai, C.Y.; Chen, W.R.; Shih, S.-M. Factors affecting wollastonite carbonation under CO₂ supercritical conditions. *Aiche J.* **2006**, *52*, 292–299. [[CrossRef](#)]
10. Ayub, S.A.; Tsegab, H.; Rahmani, O.; Beiranvand Pour, A. Potential for CO₂ Mineral Carbonation in the Paleogene Segamat Basalt of Malaysia. *Minerals* **2020**, *10*, 1045. [[CrossRef](#)]
11. Xie, H.; Tang, L.; Wang, Y.; Liu, T.; Hou, Z.; Wang, J.; Wang, T.; Jiang, W.; Were, P. Feedstocks study on CO₂ mineralization technology. *Environ. Earth Sci.* **2016**, *75*. [[CrossRef](#)]
12. Reynolds, B.; Reddy, K.J.; Argyle, M.D. Field Application of Accelerated Mineral Carbonation. *Minerals* **2014**, *4*, 191. [[CrossRef](#)]
13. Bauer, M.; Gassen, N.; Stanjek, H.; Peiffer, S. Carbonation of lignite fly ash at ambient T and P in a semi-dry reaction system for CO₂ sequestration. *Appl. Geochem.* **2011**, *26*, 1502–1512. [[CrossRef](#)]
14. Eloneva, S.; Puheloinen, E.-M.; Kanerva, J.; Ekroos, A.; Zevenhoven, R.; Fogelholm, C.-J. Co-utilisation of CO₂ and steelmaking slags for production of pure CaCO₃—Legislative issues. *J. Clean. Prod.* **2010**, *18*, 1833–1839. [[CrossRef](#)]
15. Chang, E.E.; Pan, S.Y.; Chen, Y.H.; Tan, C.S.; Chiang, P.C. Accelerated carbonation of steelmaking slags in a high-gravity rotating packed bed. *J. Hazard. Mater.* **2012**, *227–228*, 97–106. [[CrossRef](#)]
16. Liu, R.; Wang, X.; Gao, S. CO₂ capture and mineralization using carbide slag doped fly ash. *Greenhouse Gases. Sci. Technol.* **2019**, *10*. [[CrossRef](#)]
17. Gan, Z.; Cui, Z.; Yue, H.; Tang, S.; Liu, C.; Li, C.; Liang, B.; Xie, H. An efficient methodology for utilization of K-feldspar and phosphogypsum with reduced energy consumption and CO₂ emissions. *Chin. J. Chem. Eng.* **2016**, *24*, 1541–1551. [[CrossRef](#)]
18. Ding, W.; Chen, Q.; Sun, H.; Peng, T. Modified mineral carbonation of phosphogypsum for CO₂ sequestration. *J. CO₂ Util.* **2019**, *34*, 507–515. [[CrossRef](#)]
19. Power, I.M.; McCutcheon, J.; Harrison, A.L.; Wilson, S.A.; Dipple, G.M.; Kelly, S.; Southam, C.; Southam, G. Strategizing Carbon-Neutral Mines: A Case for Pilot Projects. *Minerals* **2014**, *4*, 399. [[CrossRef](#)]
20. Yang, H.; Xu, Z.; Fan, M.; Gupta, R.; Slimane, R.B.; Bland, A.E.; Wright, I. Progress in carbon dioxide separation and capture: A review. *J. Environ. Sci.* **2008**, *20*, 14–27. [[CrossRef](#)]
21. Bobicki, E.R.; Liu, Q.; Xu, Z.; Zeng, H. Carbon capture and storage using alkaline industrial wastes. *Prog. Energy Combust. Sci.* **2012**, *38*, 302–320. [[CrossRef](#)]
22. Ministry of Ecology and Environment of the People’s Republic of China. *2019 China Ecological Environment Bulletin*; 2020. Available online: <http://www.mee.gov.cn/hjzl/sthjzk/> (accessed on 30 January 2021).
23. Qi, Y.; Stern, N.; Wu, T.; Lu, J.; Green, F. China’s post-coal growth. *Nat. Geosci.* **2016**, *9*, 564–566. [[CrossRef](#)]
24. Friedlingstein, P.; O’Sullivan, M.; Jones, M.W.; Andrew, R.M.; Hauck, J.; Olsen, A.; Peters, G.P.; Peters, W.; Pongratz, J.; Sitch, S.; et al. Global Carbon Budget 2020. *Earth Syst. Sci. Data* **2020**, *12*, 3269–3340. [[CrossRef](#)]
25. Ministry of Ecology and Environment of the People’s Republic of China. *China Ecological Environment Statistics Bulletin 2016–2019*; 2020. Available online: <http://www.mee.gov.cn/hjzl/sthjzk/sthjtnb/202012/P020201214580320276493.pdf> (accessed on 7 February 2021).
26. Ministry of Ecology and Environment of the People’s Republic of China. *2020 Annual Report on Prevention and Control of Solid Waste Pollution in China’s Large and Medium Cities*; 2020. Available online: <http://www.mee.gov.cn/hjzl/sthjzk/gtfwwrfz/> (accessed on 30 January 2021).
27. Ahmaruzzaman, M. A review on the utilization of fly ash. *Prog. Energy Combust. Sci.* **2010**, *36*, 327–363. [[CrossRef](#)]
28. Gomes, H.I.; Mayes, W.M.; Rogerson, M.; Stewart, D.I.; Burke, I.T. Alkaline residues and the environment: A review of impacts, management practices and opportunities. *J. Clean. Prod.* **2016**, *112*, 3571–3582. [[CrossRef](#)]
29. Guo, J.; Bao, Y.; Wang, M. Steel slag in China: Treatment, recycling, and management. *Waste Manag.* **2018**, *78*, 318–330. [[CrossRef](#)]
30. Steel Statistical Yearbook 2020 Concise Version. Available online: https://www.worldsteel.org/en/dam/jcr:5001dac8-0083-46f3-aadd-35aa357acbcc/SSY%25202020_concise%2520version.pdf (accessed on 27 January 2021).
31. Shi, C. Steel Slag—Its Production, Processing, Characteristics, and Cementitious Properties. *J. Mater. Civ. Eng.* **2004**, *16*, 230–236. [[CrossRef](#)]
32. Pan, S.-Y.; Chung, T.-C.; Ho, C.-C.; Hou, C.-J.; Chen, Y.-H.; Chiang, P.-C. CO₂ Mineralization and Utilization using Steel Slag for Establishing a Waste-to-Resource Supply Chain. *Sci. Rep.* **2017**, *7*, 17227. [[CrossRef](#)]
33. Değirmenci, N. Utilization of phosphogypsum as raw and calcined material in manufacturing of building products. *Constr. Build. Mater.* **2008**, *22*, 1857–1862. [[CrossRef](#)]
34. Kandil, A.-H.T.; Cheira, M.F.; Gado, H.S.; Soliman, M.H.; Akl, H.M. Ammonium sulfate preparation from phosphogypsum waste. *J. Radiat. Res. Appl. Sci.* **2017**, *10*, 24–33. [[CrossRef](#)]
35. Oge, M.; Ozkan, D.; Celik, M.B.; Sabri Gok, M.; Cahit Karaoglanli, A. An Overview of Utilization of Blast Furnace and Steelmaking Slag in Various Applications. *Mater. Today Proc.* **2019**, *11*, 516–525. [[CrossRef](#)]
36. Ma, X.; Li, Y.; Qian, Y.; Wang, Z. A Carbide Slag-Based, Ca₁₂Al₁₄O₃₃-Stabilized Sorbent Prepared by the Hydrothermal Template Method Enabling Efficient CO₂ Capture. *Energies* **2019**, *12*, 2617. [[CrossRef](#)]
37. Wang, N.; Mao, M.; Mao, G.; Yin, J.; He, R.; Zhou, H.; Li, N.; Liu, Q.; Zhi, K. Investigation on carbide slag catalytic effect of Mongolian bituminous coal steam gasification process. *Chemosphere* **2021**, *264*, 128500. [[CrossRef](#)]
38. Ibrahim, M.H.; El-Naas, M.H.; Benamor, A.; Al-Sobhi, S.S.; Zhang, Z. Carbon Mineralization by Reaction with Steel-Making Waste: A Review. *Processes* **2019**, *7*, 115. [[CrossRef](#)]

39. Yongfeng, N. *Three Waste Treatment Engineering Technical Manual*; Solid Waste Volume; Chemical Industry Press Co., Ltd.: Beijing, China, 2000; ISBN 7-5025-2718-4.
40. Zhang, D.; Gao, H.; Xiao, C. *Recycling Technology of Smelting Waste Residue*; Chemical Industry Press Co., Ltd.: Beijing, China, 2018; ISBN 978-7-122-29560-6.
41. Mingxia, D.; Jinming, W.; Faqin, D.; Zhaojia, W.; Feihua, Y.; Kaibin, F.; Yu, L. Technological Mineralogical Characteristics of Phosphogypsum. *Non-Met. Mines* **2020**, *43*, 52–55. (In Chinese)
42. Xie, H.; Yue, H.; Zhu, J.; Liang, B.; Li, C.; Wang, Y.; Xie, L.; Zhou, X. Scientific and Engineering Progress in CO₂ Mineralization Using Industrial Waste and Natural Minerals. *Engineering* **2015**, *1*, 150–157. [[CrossRef](#)]
43. Li, Q.; Chen, Z.A.; Zhang, J.T.; Liu, L.C.; Li, X.C.; Jia, L. Positioning and revision of CCUS technology development in China. *Int. J. Greenh. Gas Control* **2016**, *46*, 282–293. [[CrossRef](#)]
44. 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](#)]
45. LI, B.; Bao, W.; Zheng, Y.; Zheng, K.; Tan, W. Pretreatment technology for phosphogypsum purification. *Phosphate Compd. Fertil.* **2018**, *33*, 28–31. (In Chinese)
46. Guo, R.; Chen, Q.; Huang, H.; Hu, X.; Wang, T. Carbonation curing of industrial solid waste-based aerated concretes. *Greenh. Gases Sci. Technol.* **2019**, *9*, 433–443. [[CrossRef](#)]
47. Ministry of Science and Technology of the People's Republic of China. *Roadmap for Carbon Capture, Utilization and Storage Technology Development in China*; China Science Publishing and Media Ltd. (CSPM): Beijing, China, 2019; ISBN 978-7-030-62018-7.
48. Yang, L.; Xu, M.; Yang, Y.; Fan, J.; Zhang, X. Comparison of subsidy schemes for carbon capture utilization and storage (CCUS) investment based on real option approach: Evidence from China. *Appl. Energy* **2019**, *255*, 113828. [[CrossRef](#)]
49. Yu, S.; Horing, J.; Liu, Q.; Dahowski, R.; Davidson, C.; Edmonds, J.; Liu, B.; McJeon, H.; McLeod, J.; Patel, P.; et al. CCUS in China's mitigation strategy: Insights from integrated assessment modeling. *Int. J. Greenh. Gas Control* **2019**, *84*, 204–218. [[CrossRef](#)]
50. Hillebrand, M.; Pflugmacher, S.; Hahn, A. Toxicological risk assessment in CO₂ capture and storage technology. *Int. J. Greenh. Gas Control* **2016**, *55*, 118–143. [[CrossRef](#)]
51. Yao, X.; Zhong, P.; Zhang, X.; Zhu, L. Business model design for the carbon capture utilization and storage (CCUS) project in China. *Energy Policy* **2018**, *121*, 519–533. [[CrossRef](#)]
52. Miller, J. Building a better dialogue between energy research and policy. *Nat. Energy* **2019**, *4*, 816–818. [[CrossRef](#)]
53. Li, Q.; Liu, G.; Cai, B.; Leamon, G.; Liu, L.-C.; Chen, Z.-A.; Li, X. Public awareness of the environmental impact and management of carbon dioxide capture, utilization and storage technology: The views of educated people in China. *Clean Technol. Environ. Policy* **2017**, *19*, 2041–2056. [[CrossRef](#)]