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Market Stakeholder Analysis of the Practical Implementation of Carbonation Curing on Steel Slag for Urban Sustainable Governance

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Abstract: Carbonation curing on steel slag is one of the most promising technologies for the iron and steel industry to manage its solid waste and carbon emissions. However, the technology is still in its demonstration stage. This paper investigates the market stakeholders of carbonation curing on steel slag for construction materials for its effective application by taking China as a case study. A holistic analysis of the competition, market size, and stakeholders of carbonation curing on steel slag was carried out through a literature review, a survey, a questionnaire, and interviews. The results showed that carbonation curing on steel slag had the advantages of high quality, high efficiency, low cost, and carbon reduction compared with other technologies. Shandong province was the most suitable province for the large-scale primary application of the technology. Stakeholder involvement to establish information platforms, enhance economic incentives, and promote adequate R&D activities would promote carbonation curing of steel slag into practice. This paper provides a reference for the commercialization of carbonation curing on similar calcium- and magnesium-based solid waste materials.

Keywords: mineral carbonation; carbonation curing; steel slag; market analysis; competition analysis; stakeholder analysis

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1. Introduction

Since the industrial revolution, the burning of fossil fuels has released a large amount of CO_2, which lead to global climate change and irreversible harm to the planet [1]. Currently, the global temperature has increased 1 °C compared with the preindustrial level [2]. The international community has reached a consensus to control the temperature rise below 1.5 °C by 2050 [3]. The main CO_2 management methods include enhancement of fuel utilization efficiency, application of renewable energy, and CO_2 capture, utilization, and storage (CCUS) [4].

The iron and steel industry generated 7–9% of global anthropogenic CO_2 emissions [5]. The energy-intensive industry is facing unprecedented pressure to reduce its CO_2

emissions. Meanwhile, the industry generates a large amount of steel slag, at a production rate of 280–374 Mt/y [6]. The stockpile of steel slag in the landscape has aroused serious environmental problems [7]. Steel slag contains a high weight percentage of CaO and is extremely suitable for CCUS via mineral carbonation [8]. Collaborative disposal of the gas and solid wastes in the iron and steel industry would contribute to sustainable development and governance, especially in the urban areas where most steel mills are located. Carbonation curing on steel slag for the production of building materials is one of the most promising technologies for application in iron and steel industry [9]. However, the technology has not been widely adopted in the market. Promoting the practical implementation of carbonation curing on steel slag would assist with urban sustainable development by utilizing solid wastes, reducing carbon emissions, and generating green building materials for construction.

The effective implementation of carbonation curing of steel slag requires not only high efficiency in steel slag treatment and high utilization rate but adequate information exchange [10]. Emergy analysis [11], input–output analysis [12], and material flow analysis [13] have been widely used to evaluate the implementation of various waste management technologies (e.g., biological treatment [14]) in different aspects (e.g., eco-efficiency [15]). However, these methods are not sufficient for analyzing the effective implementation of carbonation curing of steel slag, which would be based on effective collaboration among different stakeholders, including governmental supervisors, steel slag suppliers (e.g., steel firms), steel slag consumers (e.g., construction material producers), research institutes (e.g., academia), and neighboring society and local government [16]. Thus, a systematic and comprehensive study including social, economic, and environmental factors is necessary [17–19] by which decision makers can achieve a better operational performance of carbonation curing on steel slag.

Stakeholder analysis is critical in the context of sustainable development research, and particularly in environmental research. Since the mid-1980s, stakeholder analysis has been widely found in management literature. It is treated as a method for facilitating institutional and policy reform processes, because it can take all "stakes" or interests into account to incorporate all of the relevant requirements [20]. Stakeholder analysis is widely used in political, economic, and environmental research. The performance and involvement of stakeholders in waste management (i.e., stakeholders' roles [21], influences [10,22], and interests [22,23]) are identified by various assessment and rating methods [24,25] in various scales (i.e., country level, city level, sector level, and organization level). Research has indicated that stakeholders are not isolated. The sociocultural and municipal relations between stakeholders are varied [26]. Stakeholders coordinate their contributions to waste management [27]. Unlike other waste management technologies, carbonation curing on steel slag has specific features that have not yet been studied by stakeholder collaboration analysis. Stakeholders' interests, attitudes, power, knowledge, and information in regard to carbonation curing of steel slag differ from each other. Therefore, stakeholders' collaboration across different sectors in the implementation of carbonation curing of steel slag should also be mentioned.

This paper studied market stakeholders for the implementation of carbonation curing on steel slag in China, which produces nearly half of the world's steel slag and has a comprehensive utilization rate of only 30% [8]. Competition analysis in regard to carbonating curing on steel slag was carried out through comparison with commercialized CCUS technologies, steel slag utilization technologies, and cement production technologies. Then, the market size and suitable location for application of carbonation curing of steel slag were studied by surveying the amount of CO_2 emission and carbon quotas, the steel slag production rate, and the cement production capacity in each province. Furthermore, stakeholder coordination analysis was performed to increase the feasibility of policy formulation. With a holistic analysis, strategies for the promotion of carbonated steel slag building materials are provided. The results of this paper would provide a reference for the commercialization of carbonation curing technology in China.

2. Methodologies

The paper studied the potential application of carbonation curing on steel slag based on a holistic analysis of the market stakeholders, including competition analysis, market size analysis, and stakeholder analysis. Figure 1 shows the methodology in each part.

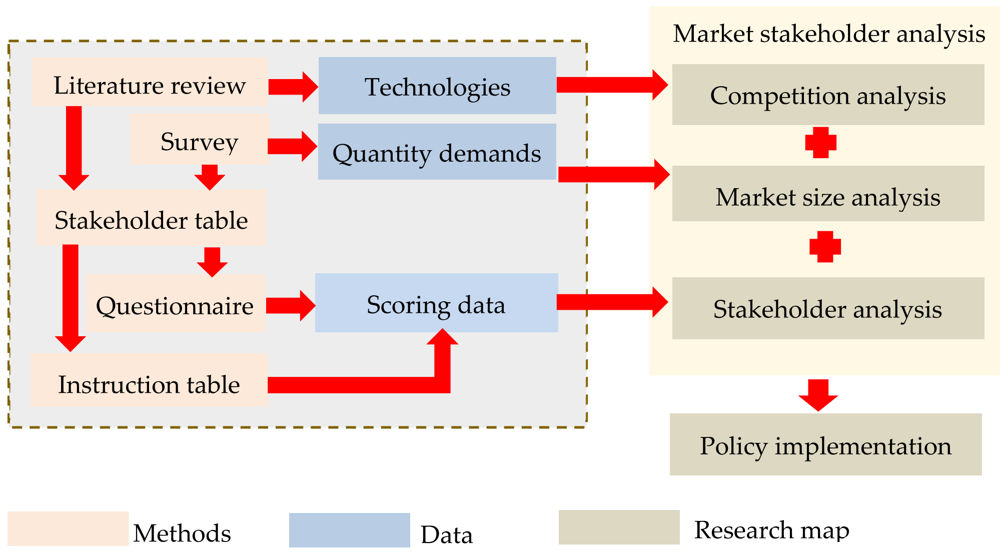

Figure 1. Method, data, and research map.

2.1. Competition Analysis

The competition analysis was based on a review of the literature on the latest technologies in carbon dioxide management, steel slag utilization, and cement production. The advantages and disadvantages of carbonation curing on steel slag were characterized through comparison with various technologies. The application directions of carbonation curing on steel slag were determined based on its features.

2.2. Market Size Analysis

The market size analysis was based on a survey of official websites and literature. The demands of CO_2 management, steel slag utilization, and cement replacement were determined at the provincial level. Suitable places for the application of carbonation curing and the size of the market were found based on the demand analysis.

2.3. Stakeholder Analysis

For stakeholder analysis, several tools and methods were introduced to gather data [28]. Similar to the methods used by Schmeer [29], Caniato et al. [30] and Wasserman and Faust [31], stakeholder tables, instruction tables, and interview questionnaires were used to obtain the primary data describing the different characteristics of stakeholders (Figure 1). Data were collected mainly from semistructured interviews.

First, stakeholders for the implementation of carbonation curing on steel slag were selected according to the literature.

Second, a snowball method was used to improve the list of stakeholders. Meanwhile, basic information on the stakeholders was gathered.

Third, semistructured interviews with stakeholders were carried out to collect the primary data. Interviews were conducted between May and July in 2021. Out of 89 invited stakeholders, 54 attended face-to-face interviews. The questions in the semistructured interviews are attached in Appendix A.

Fourth, data screening and analysis were conducted to discover the stakeholders' knowledge, interests, attitudes, and power in regard to the practical implementation of carbonation curing on steel slag under the carbon peaking and carbon neutrality goals. The roles and coordination of stakeholders during the practical implementation of carbonation curing on steel slag technology were also studied.

3. Results and Discussion

3.1. Competition Analysis

3.1.1. Literature Review of carbonation Curing on Steel Slag

The carbonation curing process is similar to the hydration curing process, but with an added CO_2 inlet in the reactor. Figure 2 shows schemes of hydration curing and carbonation curing of steel slag for building materials and their reaction mechanisms [32].

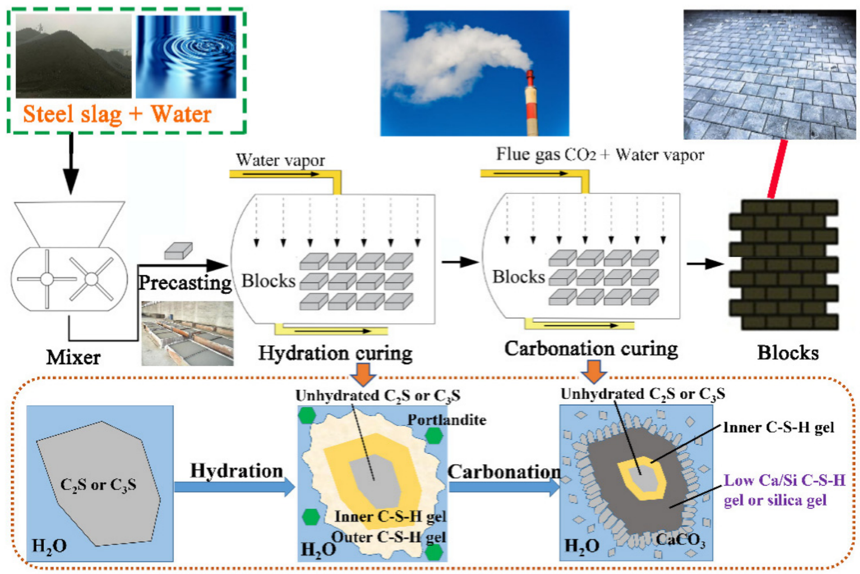

Figure 2. Hydration and carbonation curing of steel slag for building materials and their reaction mechanisms (reprinted with permission from Wang et al. [32], Copyright 2021 MDPI.).

Steel slag is composed of various calcium and magnesium minerals, which are carbonation active minerals [33]. The carbonation processes of the main minerals in steel slag are shown in reactions 1–6, including calcium and magnesium oxides (Reaction 1 and 2), hydroxides (Reaction 3 and 4), and silicates (Reactions 5 and 6). The carbonate products fill the pores between particles and consolidate the precast steel slag materials. Because of the high carbonation activity of the minerals in the steel slag, the precast steel slag materials quickly gain strength during carbonation curing [34].

Carbonation neutralizes the free oxide in steel slag and stabilizes the volume of steel slag-containing building materials [8]. Furthermore, both hydraulic and nonhydraulic calcium silicates (Reactions 5 and 6) react quickly with CO_2 and develop strength quickly at an early curing time [35]. These are the main factors that control the cements after carbonation curing.

$$CaO + CO_2 \rightarrow CaCO_3, \quad (1)$$

$$MgO + CO_2 \rightarrow MgCO_3, \quad (2)$$

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O, \quad (3)$$

$$Mg(OH)_2 + CO_2 \rightarrow MgCO_3 + H_2O, \quad (4)$$

$$3CaO{\cdot}SiO_2 + 3CO_2 + \mu H_2O \rightarrow SiO_2{\cdot}\mu H_2O + 3CaCO_3, \quad (5)$$

$$2CaO{\cdot}SiO_2 + 2CO_2 + \mu H_2O \rightarrow SiO_2{\cdot}\mu H_2O + 2CaCO_3, \quad (6)$$

The state of the art of carbonation curing on steel slag has been reviewed in many studies [36–44], which came to a common recognition that the mechanical properties and durability of carbonated steel slag materials were controlled not by the amount of CO_2 uptake but by the morphology and microstructure of $CaCO_3$ [35]. Many methods have been investigated to improve the compressive strength of the carbonated steel slag materials, including steel slag pretreatment, usage of additives, and optimization of carbonation curing conditions [9,45,46]. The purpose of these studies was to obtain the required mechanical performance of building materials at a low cost.

3.1.2. Comparison with Other CCUS Technologies

There are many CCUS methods, such as underground geological storage [47], ocean storage [48], mineral carbonation, industrial uses of CO_2 [49], and biomass storage [50]. At present, ocean storage has been avoided, because it leads to ocean acidification, which is harmful to marine organisms. Underground geological storage methods have been commercialized in many aspects, such as enhanced oil recovery (EOR) [51] and enhanced coal bed methane (ECBM) production [52,53], because of their economic benefits of incremental oil production and methane production. However, geological storage is location-oriented, and some locations may not be near sources of CO_2. Furthermore, geological storage needs careful monitoring to prevent CO_2 leakage [54].

Among all CCUS methods, mineral carbonation is the only method that can safely store CO_2 without monitoring [55,56]. In the mineral carbonation process, calcium- and magnesium-containing rocks or alkaline wastes react with CO_2 in the presence of water and form carbonates [57–61]. Mineral carbonation is extremely suitable for small or medium emitters (<2.5 Mt CO_2) [47] such as iron and steel plants. However, mineral carbonation is still in its demonstration stage because of its low reaction rate and the high cost of its accelerated measurements [62–65]. Integrating mineral carbonation into an industrial processes by using industrial alkaline wastes as cheap CO_2 feedstock is a promising strategy to reduce the production cost [66–69].

Mineral carbonation on steel slag has been studied by many researchers [70,71]. There are two main methods for mineral carbonation, direct carbonation and indirect carbonation [72]. In the indirect carbonation process, calcium ions are leached from steel slag and then precipitated as pure $CaCO_3$ [73], while in the direct carbonation process, calcium ion leaching and carbonate precipitation occur in the same container. However, the carbonated products from the direct carbonation process are in the form of a mixture, which is hard to utilize [74]. Nonetheless, carbonation curing is a direct carbonation process for the production of carbonated building materials [75]. Direct carbonation curing on steel slag is simple and chemical free. The performance of carbonated steel slag building materials is comparable to that of cement-based building materials [38]. Carbonation curing on steel slag for the production of building materials is becoming one of the most promising technologies to make mineral carbonation commercialized [9].

3.1.3. Comparison with Other Steel Slag Utilization Technologies

There are three main methods for the utilization of steel slag: aggregates for road construction, iron recycling, and filler for cement. Steel slag is abrasion resistant and thus very suitable as aggregates for road construction. This method is widely used in the United States and Europe, where the utilization rate of steel slag is nearly 100% [75]. However, use as aggregates is a low-value utilization of steel slag. Recycling iron from steel slag has higher value [76]. However, the overall economic gain is limited because of steel slag tailing becoming a new issue.

Steel slag contains a large amount of calcium silicates, like cement. However, the replacement of cement with steel slag is limited because of the latter's low hydration activity, which leads to extremely long solidification time and low early compressive strength. Furthermore, the high free calcium oxide and magnesium oxide content in steel slag could cause volume instability, which is a serious hazard for construction [77]. However, carbonation curing of steel slag could overcome all these disadvantages through its high carbonation rate and neutralization of free oxides. Moreover, steel slag is usually used as filler for cementitious materials. Since the addition of steel slag lowers the early strength of cementitious materials, the amount of steel slag has be a compromise with the mechanical performance of the building materials. However, steel slag is the main cementitious material in the carbonation curing process, which could result in high-value utilization of large amounts of steel slag.

3.1.4. Comparison with Cement

The competitive product of carbonation curing on steel slag is cement. There are two main type of cement, ordinary Portland (P.O.) cement and slag cement. P.O. cement is widely used all over the world. However, the production process of one ton P.O. cement releases nearly 0.78 t CO_2. Slag cement is composed of various solid wastes from the iron and steel industries, such as granulated blast-furnace slag and gypsum [78,79]. The mechanical performance of slag cement is similar to that of P.O. cement, while slag cement is carbon emission free. The average price of both cements has increased year by year. In 2022, the average prices of P.O. 42.5 cement and slag cement in China were 118 and 64 USD/t, respectively [16]. However, the price for steel slag powder was about 41 USD/t.

Compared with hydration curing of P.O. cement, carbonation curing of steel slag has the following advantages:

(1) Carbonation curing has a high consolidation ability. After carbonation curing for 24 h, the compressive strength of carbonated steel slag blocks reached 30–120 MPa, which was even higher than the compressive strength of hydrated steel slag products after 28 days of curing [80].
(2) The durability of carbonated steel slag material is high. The long-term volume stability of carbonated steel slag materials, which is due to the neutralization of free oxide by the chemical reaction with CO_2, has been proven in the literature [81,82]. Furthermore, the carbonated steel slag building material is resistant to the cycle of freezing and thawing because of its lack of -OH containing phases.
(3) Carbonated steel slag materials are environmentally clean. The carbonated product is mainly $CaCO_3$, which is a naturally existing, environmentally benign mineral. The carbonated building materials are pH neutral and thus extremely suitable to be used in artificial reefs for the construction of marine ranching and aquafarms [83,84]. Furthermore, carbonation could consolidate various heavy metals by turning the heavy metals ions into carbonates [85,86]. Carbonation curing could assist with hazardous waste management.
(4) Carbonation curing of steel slag yields great economic profit. The raw materials for carbonation curing on steel slag, which are solid waste materials and flue gas, are cheap. The process could also benefit from waiving of the solid waste disposal tax and carbon tax. In addition, the fraction is similar to that of the ordinary hydration

curing process. The only differences are the addition of a CO_2 inlet and gas transportation pipelines. A raw analysis showed that a 1.6 Mt C30 prefabricated building production project via carbonation curing on steel slag could generate annual profit of USD 49 million. The NPV of the project at the 3rd year could reach USD 75 million at a discount rate of 10%.

(5) The CO_2 reduction capacity of steel slag is huge. Carbonation curing of steel slag could reduce carbon dioxide emissions by two ways, direct storage of CO_2 and indirect reduction by replacement of cement. Assuming that the average weight percentage of CaO in the steel slag is 40%, and the average stoichiometric conservation of CaO in steel slag in the carbonation curing process is 35% (according to Li et al. [9,35]), the carbon sequestration potential is 94 kg CO_2/t steel slag. Assuming that the carbonation cementitious ability of steel slag is the same as the hydration cementitious ability of P.O. cement with the same weight, the replacement of cement could prevent the release of 0.78 t CO_2 per t cement during its production. If all of the annually produced 120 Mt steel slag in China were used in the carbonation curing technology to produce building materials, the theoretical reduction in CO_2 emissions would be about 104.9 Mt, including a direct reduction of 11.3 Mt and indirect reduction of 93.6 Mt.

Table 1 lists the cost, performance, pH, and carbon emissions of P.O. cement hydration, slag cement hydration, and steel slag carbonation as methods for producing cementitious materials for construction. As shown in Table 1, compared with other cements, the advantages of steel slag carbonation are low cost, high early strength, neutral pH, and carbon reduction. Although the current market share of cement production is high, carbonation curing on steel slag carbonation has significant market competitiveness under carbon management policies.

Table 1. Comparative product analysis of competitive solutions.

Competitive Product	Cost (USD/t)	Curing Time (Days)	Performance	pH	Carbon Emissions (t CO^2/t)
P.O. cement hydration	118 [a]	28	Commonly used	12–13	0.78
Slag cement hydration	64	28	Low early strength	12–13	0
Steel slag carbonation	41	1	High early strength	7–8	−0.09 [b]

Note: [a.] Calculation was based on an RMB to USD exchange rate of 0.16. [b.] Negative values represent direct CO_2 reduction potential.

However, the neutral pH of carbonated steel slag may not be applicable in some situations, such as high-performance concrete (HPC), which requires high alkalinity to protect the steel bars. Carbonated steel slag material is suitable for use in prefabricated building materials in nonbearing structures, such as square brick, pitching store, permeable brick, artificial reef, and walls. The drawbacks of carbonation curing could be overcome with the development of technology.

3.2. Market Size Analysis

3.2.1. Provinces in Urgent Need of Carbon Reduction

China has the largest carbon emissions in the world [87], and 15% of the total CO_2 emissions in China is generated from the steel industry [88]. In order to determine the provinces in urgent need of carbon reduction, the amount of carbon emissions and carbon allowance in each province of China was surveyed. Table 2 lists the carbon emissions, carbon allowance, and initial available balance of 30 provinces in China in 2017 [89]. As shown in Table 1, the top three high-CO_2 emission provinces in China were Shandong, Shanxi, and Hebei, the CO_2 emissions of which were 1446.5, 911.8, and 874.7 Mt, respectively. However, the carbon allocations of these provinces were 281.9, 59.1, and 383.5 Mt, respectively. These provinces had severe deficits from their initial available carbon balances. Xinjiang and Liaoning also had severe deficits from their initial available carbon balances due to their low allocation of carbon allowance. The amounts of the initial available carbon balances in these provinces were similar to that of Hebei. Therefore, the provinces in urgent need of reducing their CO_2 emissions were Shandong, Shanxi, Xinjiang, Hebei, and Liaoning.

Table 2. Allocation of carbon emission rights by province in China (modified from Tian and Lin [89].).

Provinces	Carbon Allowance (Mt CO_2)	Carbon Emissions (Mt CO_2)	Initial Available Carbon Balance (Mt CO_2)
Shandong	281.9	1446.5	−1164.6
Shanxi	59.1	911.8	−852.7
Xinjiang	66.9	564.1	−497.2
Hebei	383.5	874.7	−491.2
Liaoning	300.8	728.9	−428.1
Inner Mongolia	583.8	863.6	−279.8
Shaanxi	247	502	−255
Hunan	173.8	399.5	−225.7
Guizhou	90	310.6	−220.6
Ningxia	38.2	257	−218.8
Gansu	105.8	217.2	−111.4
Tianjin	69.3	173.3	−104
Fujian	199.4	282.1	−82.7
Zhejiang	405	458.7	−53.7
Chongqing	121	161.4	−40.4
Anhui	451.4	454.4	−3
Jiangsu	876.5	866.7	9.8
Guangdong	710.9	669.5	41.4
Qinghai	147.6	64.2	83.4
Henan	161.9	69.5	92.4
Jilin	396.1	265	131.1
Shanghai	414.3	261.2	153.1
Guangxi	451.5	279	172.5
Hubei	609.8	416.3	193.5
Jiangxi	485.5	275.2	210.3
Henan	913.9	630.2	283.7
Beijing	788.5	80.5	708
Heilongjiang	1170.4	405.8	764.6
Sichuan	1369.4	355.1	1014.3
Yunnan	1420.9	245.8	1175.1

3.2.2. Provinces in Urgent Need of Steel Slag Utilization

In order to analyze the provinces in urgent need of steel slag utilization, the distribution of steel mills and the production of steel slag were surveyed. Figure 3 shows the distribution of major steel mills in China [90]. As shown in Figure 3, steel mills were concentrated mainly in the east part of China. The numbers of main steel mills in Hebei, Jiangsu, and Shandong were 26, 13, and 12, respectively.

Figure 3. Steel mill distribution in China (Reproduced according to ref. [90]).

Table 3 shows the crude steel and steel slag production in each province in China in 2020 [91]. The steel slag production was calculated as 17% of crude steel production. The top five provinces in steel slag production in China were Hebei, Jiangsu, Shandong, Liaoning, and Shanxi, which produced 42.7, 20.6, 13.6, 12.9, and 11.3 Mt, respectively. Among these, Jiangsu had a light surplus in initial available carbon balance. The application of carbonation curing on steel slag in Jiangsu would not be the first choice for steel slag utilization. However, Hebei, Shandong, Liaoning, and Shanxi would be especially suitable places to adopt the technology of carbonation curing on steel slag, as it would not only provide high-value utility to their steel slag but greatly alleviate their CO_2 emission problems.

Table 3. Crude steel and steel slag production in China by province in 2020 [91].

Provinces	Crude Steel Production (Mt)	Steel Slag Production (Mt)	Provinces	Crude Steel Production (Mt)	Steel Slag Production (Mt)
Hebei	249.8	42.5	Guangxi	22.8	3.9
Jiangsu	121.1	20.6	Yunnan	22.3	3.8
Shandong	79.9	13.6	Tianjin	21.7	3.7
Liaoning	76.1	12.9	Shanghai	15.8	2.7
Shanxi	66.4	11.3	Jilin	15.3	2.6
Anhui	37.0	6.3	Shaanxi	15.2	2.6
Hubei	35.6	6.1	Zhejiang	14.6	2.5

Henan	35.3	6.0	Xinjiang	13.1	2.2
Guangdong	33.8	5.8	Gansu	10.6	1.8
Inner Mongolia	31.2	5.3	Heilongjian g	9.9	1.7
Sichuan	27.9	4.8	Chongqing	9.0	1.5
Jiangxi	26.8	4.6	Ningxia	4.7	0.8
Hunan	26.1	4.4	Guizhou	4.6	0.8
Fujian	24.7	4.2	Qinghai	1.9	0.3

3.2.3. Provinces in Urgent Need of Cement Replacement

In order to identify the provinces in China that are in urgent need of alternative cement production technologies, the clinker production of each province in China was surveyed. Figure 4 shows the cement production in each province in China in 2020 [92]. As shown in Figure 4, the provinces with cement production of more than 100 Mt/y were Jiangsu, Guangdong, Shandong and Sichuan, which had production capacities in 2020 of 136.2, 1109.6, 107.8, and 104.1 Mt/y, respectively. Among these, only Shandong was a suitable province for carbonation curing on steel slag. Hebei, Liaoning, and Shanxi were the other three provinces that most suitable for carbonation curing on steel slag; their cement production capacities were 96.4, 56.1, and 61.9 Mt/y, respectively. The cement production in these provinces was much larger than the steel slag production, which had capacities of 42.4, 12.9, and 11.3 Mt/y, respectively. Thus, the application of carbonation curing on steel slag in these four provinces could replace part of their cement production and would have a broad market space.

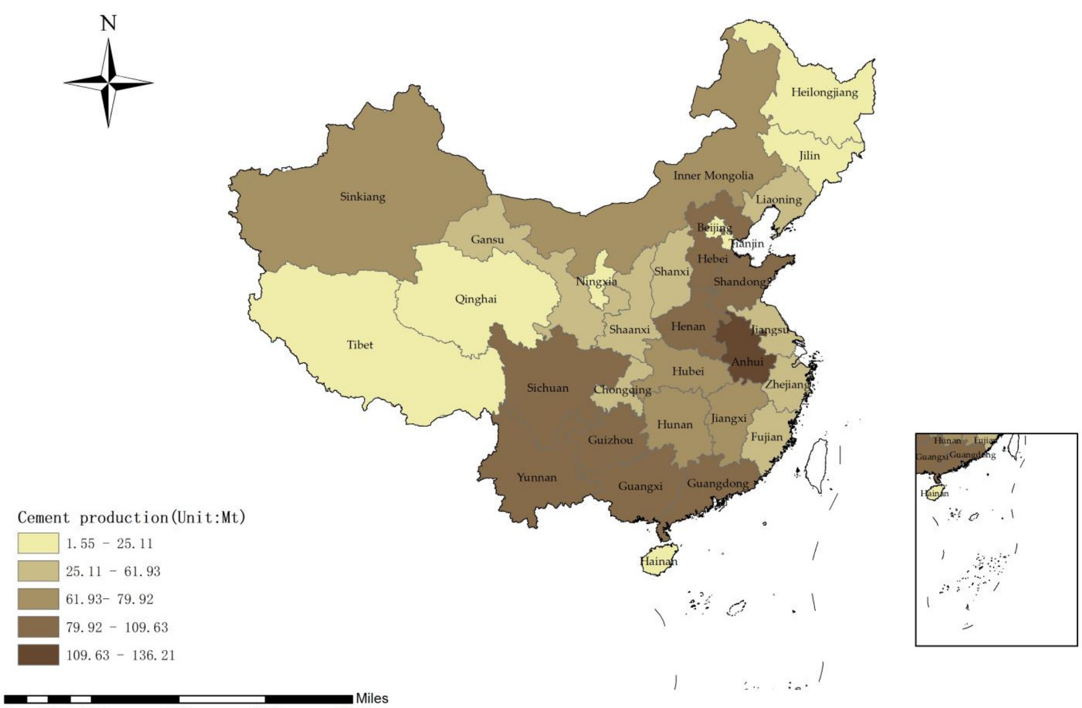

Figure 4. Cement production capacity by province in China in 2020 (Mt/y) (reproduced according to [93]).

Figure 5 shows the cement replacement capacity of the top 17 provinces in China in 2020. The cement replacement capacity is the capacity of new, reform, or expansion cement production projects announced by the Industry and Information Department in each province in 2020 and was calculated according to the capacity replacement implementation. As shown in Figure 3, Guangxi, Yunnan, Fujian, Shandong, and Sichuan were the top five cement replacement capacity provinces in China, with capacities of 8.2, 8.0, 7.6, 6.0 and 5.95 Mt/y, respectively. The cement replacement capacity in Shandong was half of its steel slag production in 2020. The promotion of carbonation curing on steel slag in Shandong could potentially replace all its cement replacement capacity for two years.

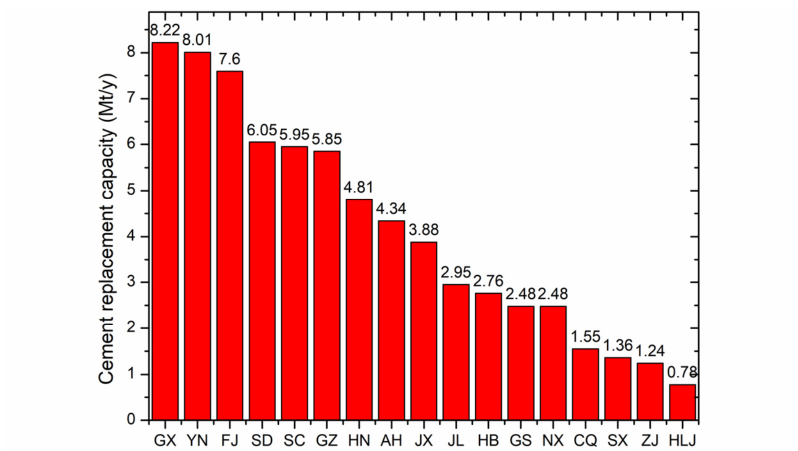

Figure 5. Cement replacement capacity by province in 2020. GX is Guangxi, YN is Yunnan, FJ is Fujian, SD is Shandong, SC is Sichuan, GZ is Guizhou, HN is Hunan, AH is Anhui, JX is Jiangxi, JL is Jilin, HB is Hubei, GS is Gansu, NX is Ningxia, CQ is Chongqing, SX is Shaanxi, ZJ is Zhejiang, and HLJ is Heilongjiang (reproduced according to [93]).

The large cement production and cement replacement production indicate that the cement demand in Shandong is large. Carbonation curing on steel slag technology may be quickly promoted to replace cement in Shandong.

3.3. Stakeholder Analysis

The interaction among stakeholders plays an important role in the implementation of the primary action to the environmental problems of the cities [94]. Stakeholder analysis involves stakeholders identification, stake holders grouping, and stakeholders investigation [95]. The stakeholders related to the practical implementation of carbonation curing of steel slag were identified from existing scientific literature and the snowball method. Stakeholders were categorized into four groups according to [96–98]. Figure 6 shows the chain of stakeholder groups of carbonation curing on steel slag according to their positions, impacts, and relationships. Group (1) comprises national and local government, which provide governance by making policies, enforcing the regulation and law; group (2) comprises iron and steel plants, which generate steel slag and CO_2; group (3) comprises building material manufacturing companies, which consume steel slag and CO_2 and produce building materials; and group (4) comprises research institutes, which provide advanced waste management technologies and strategies.

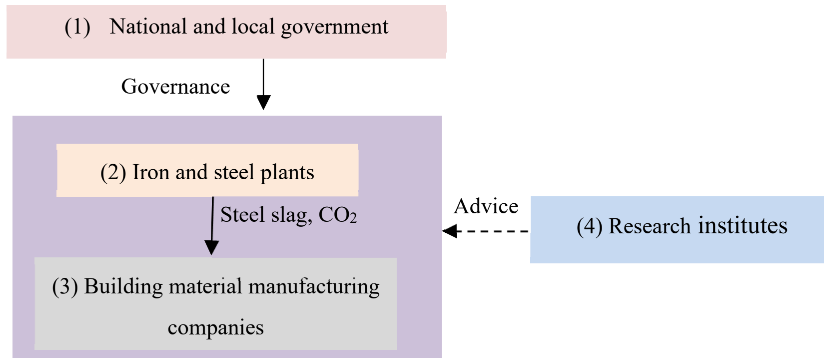

Figure 6. The chain of stakeholder categories of carbonation curing on steel slag.

The stakeholder analysis for carbonation curing of steel slag was conducted by taking Shandong as a case study. A stakeholder and instruction table for the practical implementation of carbonation curing on steel slag is shown in Table 4.

Table 4. Stakeholder and instruction table for the practical implementation of carbonation curing on steel slag.

Categories	No.	Stakeholders	Abbreviation	Roles
(1) National and local government	1	Ministry of Ecology and Environment of the People's Republic of China	MEE	Issuing regulations, making policy, supervising, licensing
	2	Department of Ecology and Environment of Shandong Province	SDEE	Granting steel slag waste management licenses, governance of environmental impact assessments (EIAs)
	3	Bureau of Ecology and Environment of Jinan	JBEE	Environmental regulation and issuing of license to the iron and steel plants in Jinan, Shandong, China
(2) Iron and steel plants	4	Jinan Iron and Steel Group Co., Ltd.	JIGANG	Production of CO_2 and steel slag
	5	Laiwu Iron and Steel Group Co., Ltd.	LAIGANG	Production of CO_2 and steel slag
	6	Qingdao Sincerely Steel Co., Ltd.	QSS	Production of CO_2 and steel slag
	7	Weifang Special Steel Group	WSSG	Production of CO_2 and steel slag
	8	Rizhao Steel Holding Group Co., Ltd.	RSHG	Production of CO_2 and steel slag
(3) Building material manufacturing companies	9	China United Cement Co. Ltd.	CUCC	Consumption of CO_2 and steel slag
	10	Sunnsy Group	SUNNSY	Consumption of CO_2 and steel slag
	11	Yizhou Group	YIZHOU	Consumption of CO_2 and steel slag
	12	Mengyin Guanghui Building Materials Co. Ltd.	MGBM	Consumption of CO_2 and steel slag

	13	Shandong Aluminum Co. Ltd.	SDALCO	Consumption of CO_2 and steel slag
	14	Tangshan Jidong Cement Co. Ltd.	JIDD	Consumption of CO_2 and steel slag
	15	Conglin Group Co. Ltd.	CONGLIN	Consumption of CO_2 and steel slag
	16	Lobe Building Materials	LOBE	Consumption of CO_2 and steel slag
(4) Research institutes	17	University of Science and Technology Beijing	USTB	Providing environmental technology, improving waste disposal technology and waste management methods
	18	Shanghai Jiao Tong University.	SJTU	Circular economy planning and design, commercial management

(1) National and local government:

The Ministry of Ecology and Environment of the People's Republic of China (MEE) is the main administrative department in charge of making policies and monitoring the emissions of steel slag and CO_2. The Department of Ecology and Environment of Shandong Province (SDEE) is in charge of granting steel slag management licenses. The Bureau of Ecology and Environment of Jinan (JBEE) is a subordinate department that communicates with SDEE about affairs related to steel slag management, such as issuing waste disposal licenses.

(2) Iron and steel plants:

Iron and steel plants are waste producers that generate CO_2 and steel slag. Iron and steel Plants in Shandong include Jinan Steel, Laiwu Steel, Qingdao Steel, Taiyuan Steel, Weifang Steel, and Rizhao Steel.

(3) Building material manufacturing companies:

Building material manufacturing companies, such as cement production companies and construction material production firms, are waste consumers. They consume the CO_2 and steel slag waste from iron and steel plants. Figure 7 shows that the major cement companies in Shandong include China United Cement Co. Ltd., Sunnsy Group, Yizhou Group, and Mengyin Guanghui Building Materials Co., Ltd. As shown in Figure 4, the cement production capacity of China United Cement Co. Ltd. and Sunnsy Group account for 47% and 25% of the provincial cement production, respectively. Collaboration with China United Cement Co. Ltd. and Sunnsy Group would assist carbonation curing on steel slag in quickly seizing the market.

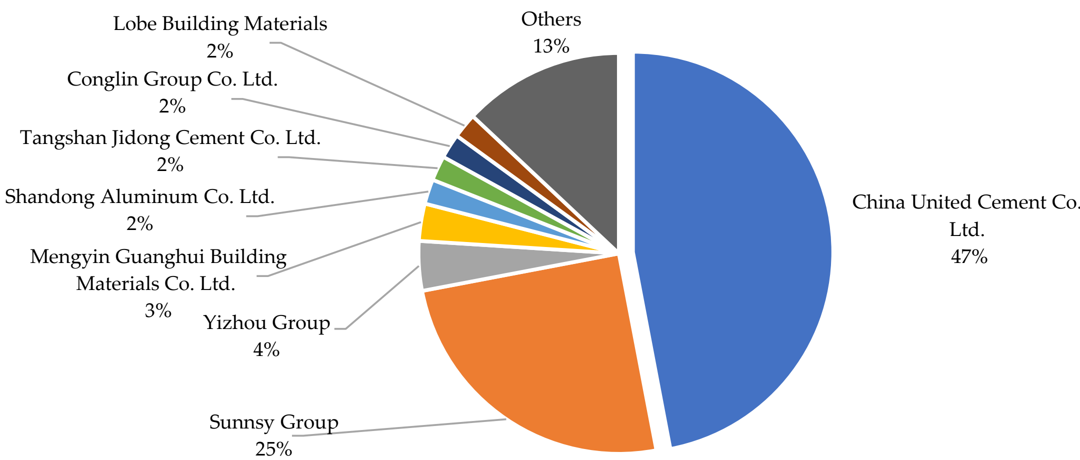

Figure 7. The output portions of major cement enterprises in Shandong.

(4) Research institutes:

Research institutes include research centers and universities, mainly the University of Science and Technology Beijing (USTB) and Shanghai Jiao Tong University (SJTU). USTB focuses on improving waste disposal technology and waste management methods, such as the R&D of the technology of carbonation curing on steel slag. SJTU concentrates on commercial management and environmental impact assessment in order to plan a circular economy for the iron and steel industry.

Stakeholder analysis was carried out on four main aspects [30], the knowledge, attitude, interests, and power of different stakeholders in regard to the implementation of carbonation curing on steel slag. The raw data were obtained by semistructured interviews based on a five-level scored questionnaire as shown in Appendix A. The purpose of stakeholder analysis was to find out the difficulties in the practical implementation of carbonation curing on steel slag. The main findings were as follows:

The local government was more interested in the technology than the national government. However, the local government had less power in practical implementation than building material manufacturing companies, as the governments were the leaders and planers but not the executors in the implementation of carbonation curing on steel slag. Among the municipal levels of government, JBEE had the highest power and should thus be a target for research institutions issuing their comprehensive knowledge on carbonation curing on steel slag.

Building material manufacturing companies had the highest power over and interest in the implementation of steel slag recycling technologies. The result was in line with Gustafsson et al. [70], who found that waste consumers had high interest and power in waste management in Sweden. However, building material manufacturing companies had limited knowledge and a conservative attitude towards emerging advanced technologies, such as carbonation curing on steel slag.

The iron and steel plants were interested in carbonation curing on steel slag because of cost saving. They had the most positive attitude and interests but less power to propose the practical implementation of carbonation curing on steel slag, because whether or not steel slag is chosen as a production material depends on the decision of building material manufacturing companies. Iron and steel plants also had absolute knowledge on carbonation curing on steel slag and were interested in investing in research and development.

The research institutes had enough knowledge of, attitude towards, and interest in the practical implementation of carbonation curing on steel slag. However, they had little power to realize the practical implementation.

4. Technology Application Suggestions

Carbonation curing on steel slag is a good technology for resource saving and carbon neutralization; however, its implementation is very difficult. In order to understand the reasons for this from a holistic perspective, sociological, economic, and ecological perspectives on the practical implementation of carbonation curing on steel slag were analyzed by a comprehensive method. The below technology application recommendations are raised.

First, stakeholders have different interests and power on practical implementation of carbonation curing on steel slag. Among all the stakeholders, building material manufacturing companies were the most influential. Unfortunately, they had insufficient drive to pursue the practical implementation of carbonation curing on steel slag due to lack of knowledge. Thus, the establishment of an information platform is necessary to allow stakeholders share their knowledge on CO_2 and steel slag management information. In this way, advanced technologies can be put into practice on time.

Second, the application of economic tools would push the practical implementation of carbonation curing on steel slag. Normally, few companies would like to manage their waste with ineffective or inefficient economic incentives. Tax policy is one of the effective economic tools and could stimulate companies to pay attention to taxed items for cost saving [28]. Carbon taxes, environmental taxes, and resource taxes could work for the implementation of carbonation curing on steel slag.

Third, supportive policies should be provided to research and development activities. Necessary funds are required to support the technology initiatives and the practical implementation of carbonation curing on steel slag. Once a successful demonstration is achieved in Shandong, the technology could spread to the other provinces in China. Therefore, sustainable development would take place in the iron and steel and building construction industries.

5. Conclusions

This paper studied the market stakeholders of carbonation curing on steel slag for construction materials production. Carbonation curing on steel slag was found to have great market potential in China through a holistic analysis of its competition, market size, and stakeholders. The detailed conclusions were as follows:

(1) Carbonation curing on steel slag is a potential replacement of cement for construction material production. Compared with other CCUS technology, it has the advantages of permanent storage of CO_2 and suitability for small or medium CCUS plants. Compared with other steel slag management methods, it stabilizes the volume of its products and enhances their consolidation ability. Compared with other cement production technologies, it has the advantages of low cost, high performance, and carbon reduction.

(2) Shandong, Shanxi, Hebei, Xinjiang, and Liaoning seriously lacked carbon emission balance. Hebei, Jiangsu, Shandong, Liaoning, and Shanxi were the top five steel slag production provinces in China. The cement production capacities of Shandong, Hebei, Liaoning, and Shanxi were much higher than their steel slag production. Shandong had the highest annual cement replacement compacity, which was twice its annual steel slag production. Shandong is especially suitable for the rapid promotion of carbonation curing on steel slag.

(3) The stakeholders for implementation of carbonation curing are governmental supervisors, iron and steel plants, building material manufacturing companies, and research institutes. Establishment of information platforms, effective economic

incentives, and adequate research and development activities would promote carbonation curing on steel slag into practice.

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

Appendix A. Interview Questionnaire

Stakeholder analysis in practical implementation of carbonation curing on steel slag
Date: ___/____/_____ ID #: _______
Organization: ____
Name: ______________________
Dear friends:

Thanks for your participation in our research. We are researchers from the University of Science and Technology Beijing and Shanghai Jiao Tong University. We're doing research to see if carbonation curing on steel slag can be done in a practical way. It's critical for us to get you and your organization's perspectives, because you are the important stakeholders in the area. We will select 89 stakeholders to interview, with questionnaires for a survey on the practical implementation of carbonation curing on steel slag. All your opinions will be used for research but not for commercial use. We will ask you some questions about your opinion on the practical implementation of carbonation curing on steel slag. Thanks for your kind participation. Please choose your score in Table A1.

Table A1. Scoring of the questionnaire for the practical implementation of carbonation curing on steel slag.

Topic	Possible Scoring	Your Score
Knowledge: Describes knowledge about practical implementation of carbonation curing on steel slag.	1. I have no idea (2) 2. Lack of knowledge (4) 3. General knowledge (6) 4. Excellent knowledge (8) 5. Comprehensive understanding (10)	
Attitude: Opinion/attitude towards practical implementation of carbonation curing on steel slag.	1. Very positive (10) 2. Positive (8) 3. Neutral (6) 4. Negative (4) 5. Very negative (2)	
Interest: The degree of stakeholders' interest in practical implementation of carbonation curing on steel slag.	1. No (2) 2. Limited (4) 3. General (6) 4. Very (8)	

	5. High (10)
Power: The power to influence and restrict other stakeholders to promote practical implementation of carbonation curing on steel slag.	1. Very low (2) 2. Low (4) 3. General (6) 4. Very (8) 5. High (10)

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