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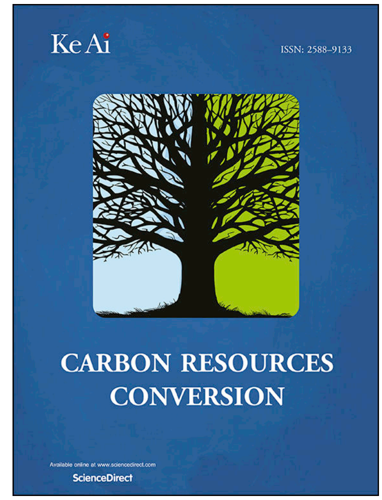

Original Article

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A Life Cycle Analysis on Magnesium Production Processes: Energy Consumption, Carbon Emission and Economics

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Abstract: Magnesium is widely used in manufacturing industry because of its excellent physical and chemical properties and has its increasing demand due to environmental requirements. China, as the world`s biggest producer and exporter of metallic magnesium, produces metallic magnesium in its western provinces through the silico-thermic process known as the Pidgeon process. However, there are few metallic magnesium plants in eastern China, especially in Liaoning province where magnesite is rich in reserves. The short supply of magnesium has limited the growth of the magnesium casting industry and the local magnesite industry. Under the carbon market established to face the challenges of climate change, how to choose an economical and feasible route for magnesium production, is a key factor to determine the development of magnesium industry in Liaoning. In this paper, life cycle analysis models are developed to study the energy consumption, greenhouse gas (GHG) emissions, and economics from cradle to gate for six different metal magnesium production processes using data accounting for different geographical environments, process equipment, and energy supply pathways based on the Chinese Life Cycle Database (CLCD). The influence of carbon trading prices on economic performance of the six processes is also investigated. Compared with the current process widely used in China, the new magnesium production technology using Liaoning`s abandoned magnesite as raw material and the coke oven gas from steelworks as fuel showed the best economic performance in terms of cost for greenhouse gas emissions.

Keywords: Magnesium, Pidgeon process, Thermal reduction, Life cycle, Greenhouse gas emission.

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1. Introduction

Magnesium, a light silver-white alkaline earth metal and widely distributed in nature, has active chemical properties, certain ductility, and heat dissipation. It is the eighth-most abundant element in the earth`s crust and the lightest structural metal [1]. During WWII, the magnesium industry grew rapidly, and the metal was widely used in fighter manufacturing in Germany because of its lightweight [2]. After the war, magnesium was gradually used in civilian applications [3], including the production of aluminum alloy, the production of magnesium alloy, titanium sponge, and steel desulfurization [4]. Magnesium can also be used in rare earth alloys, metal reduction, corrosion protection, and other fields [5], [6]. The magnesium alloy features low density, high specific strength, high shock and dent resistance [7], [8], and thus has been widely used in 3C consumption, electronic industry, medical care, military projects, aviation, rail transit, and automobiles [9]–[11]. In particular, the application of magnesium alloys in vehicles attracted much attention due to the need for lightweight vehicles. Because of the low-density characteristic of magnesium alloy, the introduction of magnesium alloy into automobiles can effectively reduce the energy consumption and greenhouse gas emissions [12], [13]. However, the metallic magnesium production process in China has been criticized for its high environmental burden [4].

There are two main ways to produce magnesium in industry, i.e., electrolysis and silicon thermal reduction [14]. According to the process characteristics, the silicon thermal reduction method has three alternatives: the Pidgeon process, the Bolzano process, and the Magnetherm process [4], [15]. Among these processes, the Pidgeon process which was invented by Dr. Pidgeon in the early 1940s [16] is the simplest, with less investment, and has been widely developed in China since 1988 [17]. The Pidgeon process had beeen applied in nearly all the Mg production plants in China. China is now the world`s biggest producer of magnesium, almost all of which is produced using the Pidgeon process. In 2018, global magnesium production reached 970k tons, of which 82.5% was contributed by China (MIIT，PRC, 2019). In China, the Pidgeon process operates in batch mode at elevated temperatures (about 1200 ^{o}C) and extract magnesium in the form of vapour from dolime (MgO·CaO) by a silico-thermic reduction reaction under a vacuum condition in an externally heated retort. Commonly, the dolomite is crushed into small pieces and then calcined in a rotary kiln at 1100-1300 ^{o}C for several hours to form dolime. Both silicothermic reduction and the carbonate decomposition are endothermic reactions, so the energy consumption of magnesium production is very high. A large amount of GHG emissions are emitted because the fossil fuels are used in the calcination and reduction stages of magnesium production [18]. These environmental problems have seriously limited the development of China`s metallurgical magnesium production under the pressure of climate change and the China`s carbon-neutral target. In 2020, the Ministry of Industry and Information Technology of China issued specifications and conditions for the magnesium industry, which set strict limits on energy consumption, equipment, and resource utilization rates for the magnesium industry, to change the current situation of high energy consumption and high pollution.

To solve the problem of energy conservation and GHG emissions in metallic magnesium production, we developed a number of magnesium production processes using fluidized bed technology. In these processes, the thermal decomposition of the carbonate occurs in a transport fluidized bed rather than in a conventional rotary kiln. In a transport fluidized bed, the raw material is ground into fine particles to achieve the fluidization. Compared with rotary kiln, transport fluidized bed can decompose carbonate in a few seconds at lower temperature due to reduced particle size and the improved heat transfer efficiency, thus reducing the energy consumption and GHG emissions [19]. In addition to dolomite, a low-rank magnesite from Liaoning province is also considered to be an ideal Mg resource due to its high Mg content and zero cost. Besides the traditional ferrosilicon reductant, aluminum is used as the reductant too because of the high magnesium yield by the alumino-thermic process during the reduction stage (Deng et al., 2014). In addition, the environmental burden of the process is also affected by the fuel selection strategies. Based on transport fluidized bed technologies, five different metallic magnesium production processes have been established considering different geographical environments, magnesium sources, reductants, and energy supply pathways. It`s essential and necessary to comprehensively evaluate these five alternatives in order to determine whether the alternative processes are really energy efficient and environment friendly, so as to select the best process while the economic performance can not be neglected.

Life cycle assessment (LCA) is a holistic and powerful method for analyzing the environmental impacts of technology process, activity, or product during their life cycle [22], [23]. LCA is an appropriate approach, which takes into account different emissions of all materials and processes and provides a vital guidance for improving the performance from the environmental point of view through evaluating energy flow extensively [24]–[26]. Over the years, researchers have used LCA to investigate the environmental impacts from primary magnesium production [4], [27]–[31]. S and P [28]compared the emission of kg CO_2-eq per unit weight of magnesium ingots produced by electrolysis and Pidgeon processes. Cherubini et al. [4] conducted a life cycle analysis of carbon emission for different magnesium production routes. Gao et al. [27] assessed the GHG emissions for the Pidgeon process and compared three scenarios with different fuels as energy sources.

The “cradle to gate” life cycle assessment is therefore used to focus on the economic, energy and environmental aspects of these five metallic magnesium production processes and the Pidgeon process. The first objective of this paper is to compare the Pidgeon process with alternative processes evaluated by LCA and to determine which process is the most environment-friendly and cost-saving, so as to provide a reference for upgrading the metallic magnesium production industry. The second objective is to establish a life cycle mode of the current Pidgeon process in China based on the Chinese life cycle database (CLCD) completely, which can be used for future related research and upgrade of the basic LCA database. This work is aimed at providing useful insight for the sustainable development of magnesium industries and the proper route selection.

2. Methodology

Fugu County, located in Shaanxi Province of China, is an essential magnesium smelting base and the largest industrial cluster of magnesium smelting enterprises in China and even the world. In 2019, Fugu's magnesium production accounted for more than 50% in China and 40% in the world. The production technology adopted in Fugu can be considered the most representative in magnesium production globally. For this reason, we chose the Pidgeon process used in Fugu as our research object and developed a life cycle model to assess the Pidgeon process based on the actual process data provided by the local authorities. The data was obtained by averaging the actual production data of a number of enterprises under the jurisdiction of the local authorities. Then, we established the life cycle assessment models for the other five alternative processes with reference to the Pidgeon process model according to the energy-material flow and energy-material conservation principle. The six models were computed by eFootprint, an online life cycle assessment platform based on the CLCD. From the results, the energy consumption, carbon emission, and economics of the life cycle magnesium production processed can be evaluated quantitatively and precisely.

In this work, we followed the ISO guidelines, which consist of four steps: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation.

2.1. Goal and scope definition

The goal of this work is to evaluate the environmental and economic impacts of the Pidgeon process and other five alternatives for the production of primary magnesium in order to assess the environmental and economic feasibility of alternative processes. The assessment system boundaries of all the six processes are defined as “cradle to gate”, including all the phases involved from mining of raw materials to final products.

The assessment system includes raw ores mining, transportation, reductant production, primary magnesium production, fuel production and all the auxiliary systems related to environmental impacts, such as power generation and coal mining & processing. The functional unit is the production of 1 tone of Mg ingots in this study.

2.2. Scope of Pidgeon process

The life cycle of Pidgeon process in Fugu, shown in Fig. 1, includes eight stages: transportation, coal mining & processing, semi-coke gas production, dolomite mining, ferrosilicon production, fluorite production, Mg production and electricity production.

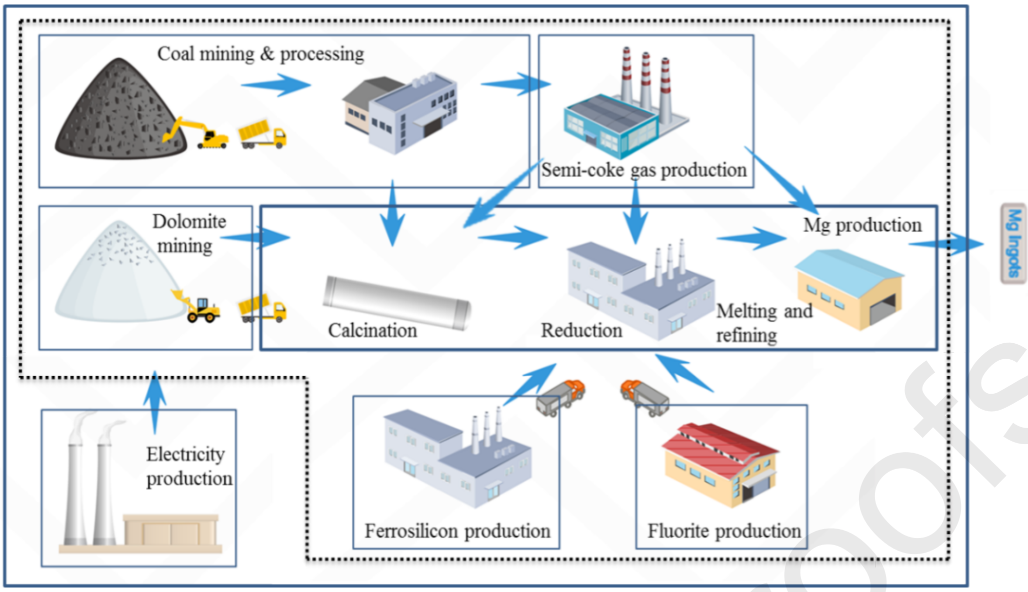

Fig. 1. Life cycle of Mg ingots production in Fugu.

Transportation. All the transportation activities within the system scope were included. But only long-distance transportation is considered while transportation between the production departments is ignored in the analysis. Dolomite ore and ferrosilicon are trucked from neighboring Shanxi province to the calcination and reduction departments of the Mg plant, respectively, with an average distance of 50 km. Fluorite ore is delivered by truck an average of 100 km from Inner Mongolia to the reduction department of the Mg plant. The coal plant and the Mg plant are close, so the transportation between them is ignored. The semi-coke gas is piped a short distance to the reduction department, and the washed coal is sent to the plant on belt conveyors, so the transportation of semi-coke gas and washed coal is omitted too. All the road transportation is fueled with diesel.

Coal mining and processing. Raw coal is mined and transported to the coal washing plant, where it is washed according to the quality requirements. On average, 1.21 ton of raw coal produces 1 ton of washed coal with an consumption of 7.27 kWh of electricity.

Semi-coke gas production. The washed coal is fed into a coke oven to produce semi-coke and semi-coke gas. In this process, the production of 1.0t semi-coke, 0.101t coal tar and 1.479t semi-coke gas consumes 1.65t washed coal, 125 kWh electricity and 0.594t semi-coke gas. The semi-coke gas is cooled and purified, and is further used as fuel for reduction, melting and refining in the magnesium plant. The semi-coke gas production is a multi-output system, and the allocation of energy consumption and emission in the system are considered in order to determine the environmental effect of semi-coke gas precisely. With the mass allocation method, the allocation factors of the semi-coke and the semi-coke gas are calculated as 38.76% and 57.33%, respectively.

Dolomite mining. Dolomite ore is the principal raw material, mined and transported to the Mg plant. It takes 11 tons of ore to produce 1 ton of Mg.

Ferrosilicon production. The ferrosilicon, containing 75% silicon and 25% iron, is used as the reductant in the reduction process. Ferrosilicon is produced in three-phase submerged arc furnaces by the carbo-thermic reduction of silica in the presence of high-quality scrap steel with an extensive power consumption. 1.06 tons of ferrosilicon is needed to produce 1 ton of Mg.

Fluorite production. Fluorite is mined and transported to the Mg plant. 0.15 tons of fluorite is need to produce 1 ton of Mg.

Mg production. The dolomite is calcined in a rotary kiln at a high temperature ranging from 1150 to 1250 °C. The major ingredient $CaCO_3 \cdot MgCO_3$ is decomposed into MgO and CaO (i.e. dolime), and CO_2 is released during the calcination process. Semi-coke gas and coal powder are used as fuel for calcining dolomite. The dolime, ferrosilicon, and fluorite are grounded separately and mixed in specific proportion. The mixture is pressed into briquettes and used as the feedstock for the reduction process. They are fed into the horizontal pots in a furnace heated externally by the semi-coke gas at a temperature of about 1200 °C and a vacuum pressure of 10 Pa. The magnesium is reduced to vapor which is condensed into crown crystal on the recyclable water-cooled head of the pot. The crown magnesium obtained from the reduction process is then melted in a melting furnace and refined by heating the melt above the melting point of 740 °C. Finally, the molten magnesium is cast into magnesium ingots. The semi-coke gas was used as the fuel in this refining process.

Electricity production. Electricity is taken from the Northwest China power grid and transmitted to the magnesium plant.

2.3. Description of Mg production processes scenarios

Currently, the Mg can be produced by several alternative processes, although the Pidgeon process is mainly employed in China. In order to gain insights into improving the performance of Mg production, all these alternative processes are evaluated in this study on the basis of the same conditions of Pidgeon process， as shown in Fig. 2. In these processes, combined with the actual situation in Liaoning, three strategies for energy saving and CO_2 reduction are introduced, including the selection of reducing agents, the upgrading of calcination equipment, and the change of fuel gas.

The differences among the six Mg production processes scenarios are mainly in the stage of Mg production. Scenario 1 is the Pidgeon process and has been previously discussed. Scenario 2 introduces a transport fluidized bed to calcine dolomite rather than the traditional rotary kiln. In scenario 3, the limestone and magnesite ores are used as the raw materials to produce Mg with aluminum reductant [32], [33]. Aluminum of 99% purity is used as the reductant and 2 wt% CaF_2 is added. Magnesite with 46 wt% MgO and limestone (52 wt% CaO) are the resource of magnesium. The transport fluidized bed is used as calcination equipment and the producer gas is used as fuel gas. Scenario 4, based on Scenario 3, uses the coke oven gas from the steelworks as fuel. In scenario 5, the transport fluidized bed is used to calcinate the raw ore particles. Grade 3 magnesite (43 wt% MgO), normally discarded as solid waste in Liaoning, and limestone (52 wt% CaO) are used as feedstocks to produce dolime during the calcination stage. Producer gas was used as fuel gas. Scenario 6, based on scenario 5, uses coke oven gas for the energy supply of the system. It is worth noting that scenario 3, 4, 5, and 6 are suitable for Liaoning province due to its extremely rich magnesite resources.

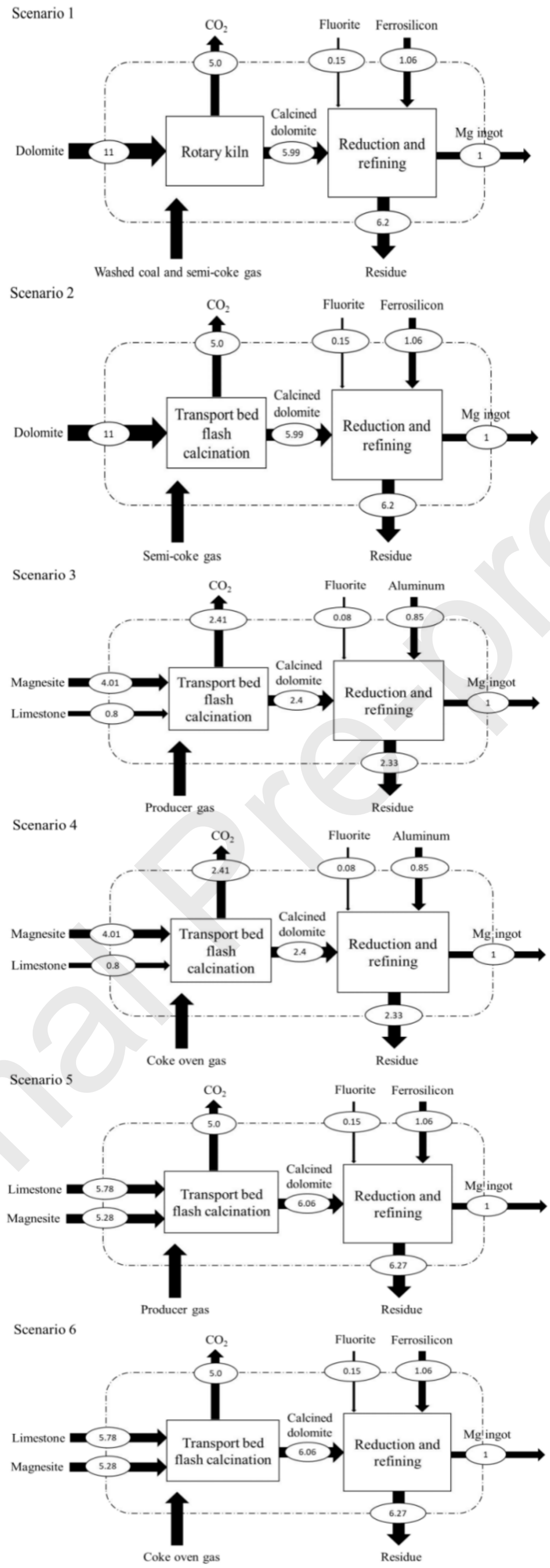

Fig. 2. System boundaries and mass flow of six Mg ingot production scenarios (unit: t).

2.4. Life cycle inventory (LCI)

The foreground data of raw materials and energy inputs in scenario 1 comes from Fugu authorities (Shaanxi, China), representing the average production level of local Mg plants. The foreground data of raw materials and energy consumption in other scenarios are calculated based on the principles of conservation of mass and energy using the relevant data from published studies, patents, and comparisons with the silicon-thermic process [34], [35]. The detailed data is presented in Fig. 2 and Table 1. The background data is retrieved from the China life cycle database (CLCD) in the software ebalance. Transportation for all scenarios is determined by the location of the source of raw materials and fuel. Electricity consumption in all the scenarios is assumed to be the same, since electricity is consumed primarily for utilities.

Table 1. LCI of Mg production scenarios for 1 tone Mg ingot.

Item	Unit/tonnes$_{Mg}$	Scenarios					
		S1	S2	S3	S4	S5	S6
Mg ingots production							
Dolomite	tonnes	11	11				
Limestone				0.8	0.8	5.78	5.78
Magnesite	tonnes			4.01	4.01	5.28	5.28
Ferrosilicon	tonnes	1.06	1.06			1.06	1.06
Aluminum	tonnes			0.85	0.85		
Fluorite	tonnes	0.15	0.15	0.08	0.08	0.15	0.15
Washed coal	tonnes	1.5					
Semi-coke gas	m^3	16000	14308				
Producer gas	m^3			12252		19547	

Coke oven gas	m^3				4039		6444
Electricity	kWh	1200					
Road transportation	t·km	618	618	179	370	754	734
Railway transportation	t·km					1378	1336
Product							
Mg ingots	tonnes	1.00					

2.4. Life cycle impact assessment (LCIA)

The LCIA is used for quantitative analysis of the possible environmental impacts, such as resource and energy consumption, ecological damage, human health damage, based on the life cycle inventory [36], [37]. The LCIA method adopted by eFootprint platform is a comprehensive evaluation index based on the mid-point method according to China`s energy conservation and emission reduction policy objective [38]. The selected mid-point categories are global warming potential (GWP, kg CO_2 eq.), primary energy demand (PED, MJ), resource depletion-water (WU, kg), acidification (AP, kg SO_2 eq.), abiotic depletion potential (ADP, kg Sb eq.), eutrophication (EP, kg PO_4^{3-} eq.), particulate matter (RI, kg PM2.5 eq.), Ozone depletion (ODP, kg CFC-11 eq.), and photochemical ozone formation (POFP, kg NMVOC eq.).

This study takes primary energy demand and global warming potential as environmental indicators to evaluate energy consumption and greenhouse gas emissions of the six scenarios. The results are calculated based on the background data of the scenarios and the corresponding parameters in the CLCD. Note that the life cycle GHG emissions released throughout the scenarios can be divided into direct carbon emissions and indirect carbon emissions. The GHG emissions from the combustion of fuels and the decomposition of raw carbonate ores belong to direct carbon emissions, while other GHG emissions from the upstream processes are considered indirect carbon emissions.

The GHG emissions emitted from carbonate ores calcination are calculated by the following equation.

$$E_{DC} = M_1 \times \frac{44}{40} + M_2 \times \frac{44}{56}$$

Where M_1 is the quantity of MgO, M_2 is the quantity of CaO and E_{DC} represented GHG emissions emitted from the dolomite calcination process.

The GHG emissions associated with fuel combustion are estimated by the following equation.

$$E_{FC} = \frac{44}{12} MQK\alpha$$

Where, E_{FC} is the GHG emission quantity from fuel combustion (kg CO_2 -eq), $\frac{44}{12}$ is the molecular mass ratio of carbon dioxide to carbon, M is the fuel consumption (kg), Q is the calorific value of fuel (MJ/kg), K is the carbon emission coefficient of fuel combustion (kg C/MJ) and α is the carbon oxidation ration of fuel (%). The parameter values of the washed coal are listed in Table 2. The GHG emissions of the fuel gases combustion are calculated according to their composition, as shown in Table 3.

Table 2. The parameter values of washed coal.

Fuel	Q (MJ/kg)/(MJ/m^3)	K (kg C/MJ)	α (%)
Washed coal	26.4	25.8×10^{-3}	1

Data comes from IPCC 2006

Table 3. The characteristics of fuel gases.

Gas	Component (V %)							Calorific value (MJ/m^3)
	H_2	CH_4	CO	N_2	CO_2	CmHn	O_2	
Semi-coke gas	27	7.5	11.5	45.5	7.5	0.3	0.7	7.75
Coke oven gas	55	24	14.5		3.5	2.3	0.1	16.35
Producer gas	13	2.2	27.5	51.8	5	0.3	0.2	5.39

2.5. Production cost of Mg production

The total production costs include the cost of the raw ore (dolomite, magnesite, and limestone), the catalyst (fluorite), the fuel (coal and fuel gasses), the reductant (ferrosilicon and aluminum), the utilities (electricity), and the lost reduction pots. Mg production cost are estimated based on raw material price in China in 2019 published by Metal news, as shown in Table 4. Due to the limited material technology, the reduction pot has a relatively short service life and is replaced frequently during the Mg production period, so the cost of the reduction pot needs to be considered. Meanwhile, the impact of

283 GHG emissions on the economy is studied by monetizing GHG emissions in the carbon
284 trading markets in China and the European Union (EU).

285 Table 4. The raw material prices of Mg production.

Specie	List	Price
Raw ore	Dolomite	100 ¥/t
	Magnesite	10 -400 ¥/t
	Limestone	100 ¥/t
Catalyst	Fluorite	1800 ¥/t
Fuel	Washed coal	500 ¥/t
	Semi-coke gas	0
	Producer gas	0.28 ¥/m^3
	Coke oven gas	0
Reductant	Ferrosilicon	5750 ¥/t
	Aluminum	14420 ¥/t
Power	Electricity	0.75¥/kWh
Equipment loss	Reduction pot	3600 ¥/t Pidgeon Mg
Carbon cost	CO_2 emissions	53 - 191 ¥/t CO_2-eq

286

3. Results and Discussion

3.1. Analysis of LCA results in S1 (Pidgeon process)

The calculated PED and GWP results of S1 are listed in Table 5. To examine the individual contribution of each life cycle inventory of S1, the relative contribution (%) of each item to the selected environmental impact categories is shown in Fig. 3.

Table 5. Life cycle PED and GWP results of S1 (Pidgeon process).

Item	PED (MJ)	GWP (kg CO_2 eq.)	
Dolomite	760	59.6	
Ferrosilicon	$1.92x10^5$	$1.47x10^4$	
Fluorite	139	10.4	
Washed coal	$4.49x10^4$	296	
Electricity	$1.4x10^4$	$1.08x10^3$	
Semi-coke gas	$3.86x10^5$	$6.09x10^3$	
Transportation	347	36	
Washed coal combustion		$3.75x10^3$	
Semi-coke gas combustion		$8.32x10^3$	Direct emissions $1.71x10^4$
Dolomite decomposition		$5x10^3$	
Total	$6.38x10^5$	$3.93x10^4$	

It shows that for 1 ton Mg produced, the energy consumption and the GHG emissions are $6.38x10^5$ MJ and $3.93x10^4$ kg CO_2-eq., respectively. Ehrenberger Simone has conducted a detailed carbon footprint study of magnesium and its application in automobiles[30], [39]. Their work is greatly appreciated and serves as a guidance document recommended by the International Magnesium Association. Based on their research, from a cradle to gate perspective, the overall average emissions of the magnesium production in China amount to 28 kg CO_2-eq. per kg magnesium (including all upstream processes) of which the carbon emissions of the semi-coke gas-fueled process amount to about 19 kg CO_2-eq. per kg magnesium.In their study, they suggested that the semi-coke gas could be credited to the magnesium production system, as the gas would be released into the atmosphere if not used, with a credit of about 9 kg CO_2-eq. In fact, due to the large-scale use of semi-coke gas in the magnesium production, the production of semi-coke gas has become a matching process for the production of magnesium, hence we do not credit semi-coke gas in this paper. In the Pidgeon process without upstream processes, the carbon emissions result calculated by Ehrenberger Simone is 12.1 kg CO_2-eq, and our result is 17.1 kg CO_2-eq. This is because the magnesium enterprise in Fugu uses extra coal powder besides the semi-coke gas to calcinate dolomite, which can be found in the life cycle list above. In addition, in the production of ferrosilicon, Ehrenberger Simone considers a carbon emission of 12.5 kg CO_2-eq, whereas we consider it to be 14.7 kg CO_2-eq. This is because Ehrenberger Simone adopted the value of advanced ferrosilicon production processes, while we adopted the average value of Chinese ferrosilicon enterprises. The remaining value discrepancy is caused by the difference between the Ecoinvent database and the CLCD used for the background data.

As shown in Fig 3(a), the combustion of washed coal and semi-coke gas contributes 30.70%， and the decomposition of dolomite 12.72% to the total GHG emissions. This indicates that the carbon footprint of S1 comes mainly directly from the combustion of fuel. The productions of ferrosilicon, semi-coke gas, and electricity emit indirectly 37.31 %, 15.4%, and 2.76%, respectively. The GHG emissions from dolomite, fluorite, washed coal, and transportation are low and can be ignored. Regarding PED, it`s found that the ferrosilicon, the semi-coke gas, and washed coal are the main contributors, and the contribution of dolomite, fluorite, and transportation could be ignored because of their tiny shares (<1%), as shown in Fig. 3(b). It is apparent that energy-saving measures should be taken in energy utilization and ferrosilicon production processes so that PED can be effectively reduced.

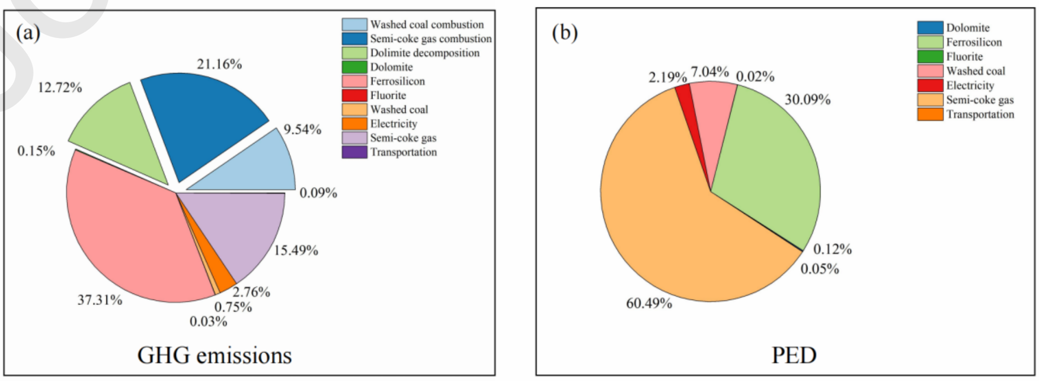

Fig. 3. Relative contribution of each life cycle inventory to GWP (a) and PED (b) in SI (Pidgeon process).

3.2. Comparison of LCA results among all scenarios

A comparative life cycle analysis on GWP and PED of metallic magnesium production from the Pidgeon process and five other alternative processes is conducted by the online eFootprint platform based on the CLCD. The calculated results are presented in Tables 6 and 7, and Fig. 4.

Table 6. Comparative analysis of the six metallic magnesium production scenarios in global warming potential.

Item		GWP (kg CO_2 eq.)					
		S1	S2	S3	S4	S5	S6
Carbonate ore	Dolomite	59.6	59.6				
	Magnesite			21.7	21.7	28.6	28.6
	Lime			4.33	4.33	31.3	31.3
Reductant	Ferrosilicon	1.47×10^4	1.47×10^4			1.47×10^4	1.47×10^4
	Aluminum			1.93×10^4	1.93×10^4		
Fluorite		10.4	10.4	5.56	5.56	10.4	10.4
Fuel	Washed coal	296					
	Coke oven gas				1.21×10^3		1.93×10^3
	Producer gas			2.97×10^3		4.74×10^3	
	Semi-coke gas	6.09×10^3	5.48×10^3				
Electricity		1.08×10^3	1.08×10^3	1.08×10^3	1.08×10^3	1.08×10^3	1.08×10^3

Transportation	Road	36	36	10.4	21.6	43.9	42.7
	Railway					14.1	13.7
Direct contribution	Carbonate decomposition	$5x10^3$	$5x10^3$	$2.41x10^3$	$2.41x10^3$	$5x10^3$	$5x10^3$
	Fuel combustion	$1.21x10^4$	$7.45x10^3$	$8.35x10^3$	$3.51x10^3$	$1.33x10^4$	$5.61x10^3$
Total		$3.93x10^4$	$3.38x10^4$	$3.42x10^4$	$2.76x10^4$	$3.89x10^4$	$2.84x10^4$

338 Table 7. Comparative analysis of the six metallic magnesium production scenarios
339 in primary energy demand.

Item		PED (MJ)					
		S1	S2	S3	S4	S5	S6
Carbonate ore	Dolomite	760	760				
	Magnesite			277	277	365	365
	Lime			55.3	55.3	399	399
Reductant	Ferrosilicon	$1.92x10^5$	$1.92x10^5$			$1.92x10^5$	$1.92x10^5$
	Aluminum			$2.27x10^5$	$2.27x10^5$		
Fluorite		139	139	74.2	74.2	139	139
Fuel	Washed coal	$4.49x10^4$					
	Coke oven gas				$1.06x10^5$		$1.7x10^5$

		S1	S2	S3	S4	S5	S6
	Producer gas			1.19×10^5		1.9×10^5	
	Semi-coke gas	3.86×10^5	3.47×10^5				
Electricity		1.4×10^4	1.4×10^4	1.4×10^4	1.4×10^4	1.4×10^4	1.4×10^4
Transportation	Road	347	347	101	208	423	412
	Railway					176	170
Total		6.38×10^5	5.54×10^5	3.61×10^5	3.48×10^5	3.98×10^5	3.77×10^5

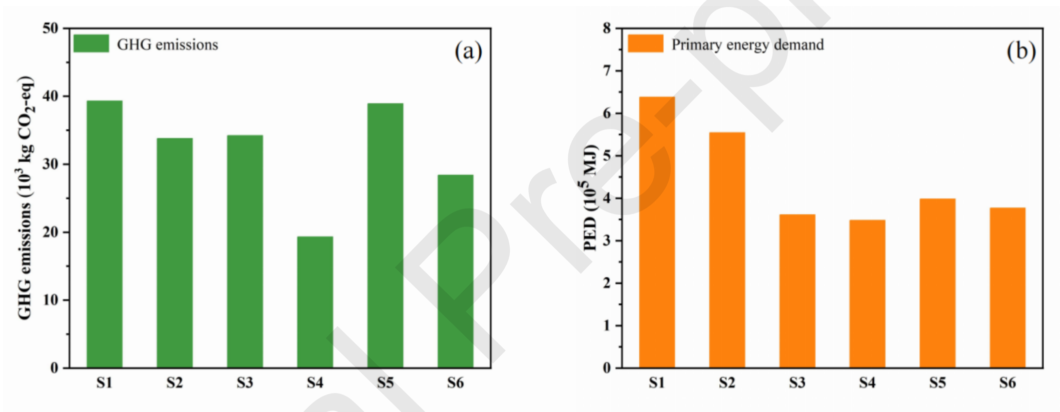

Fig. 4. GWP (a) and PED (b) results of the six scenarios.

For the six metallic magnesium production scenarios, carbon emissions are dominated by carbonate ore decomposition, fuel combustion, and the preparation of reductant. The energy is mainy consumed in the productions of reductant, fuels, and electricity in these six scenarios.

It can be seen that to produce 1 ton Mg product, the process order in terms of GWP is as follow： S1 (3.93×10^4 kg CO_2-eq) > S5 (3.89×10^4 kg CO_2-eq) > S3 (3.42×10^4 kg CO_2-eq) > S2 (3.38×10^4 kg CO_2-eq) > S6 (2.84×10^4 kg CO_2-eq) > S4 (2.76×10^4 kg CO_2-eq). In terms of energy consumption, the order is S1 (6.38×10^5 MJ) > S2 (5.54×10^5 MJ) > S5 (3.98×10^5 MJ) > S6 (3.77×10^5 MJ) > S3 (3.61×10^5 MJ) >S4 (3.48×10^5 MJ). It indicates that S4 has the lowest energy consumption and carbon emissions for the production of Mg. It shows that S1 and S5 are close in GHG emissions, but S1 consumes significantly greater energy than S5.

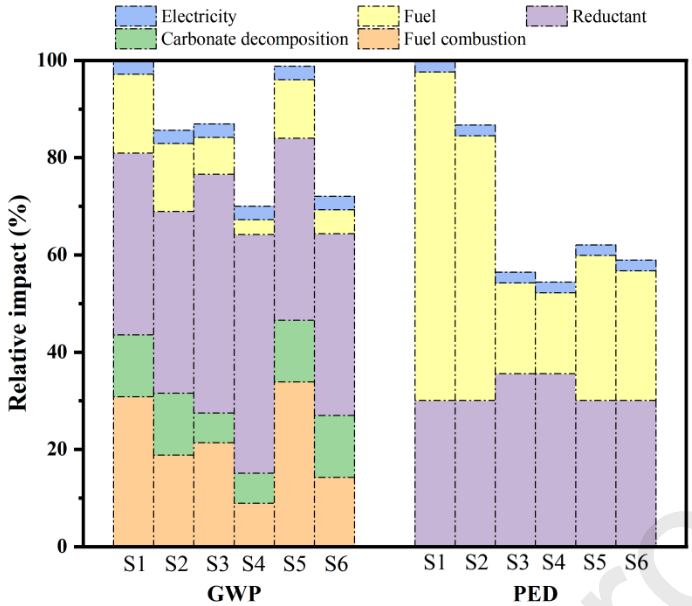

Fig. 5. Comparative GHG emissions and PED results for the six scenarios (Note: in the figure, the highest impact was defined as 100%, and each bar represented the relative percent to the highest score).

In order to further identify the share of each life cycle inventory to the overall GWP and PED of the six scenarios, the contribution (%) of each item is estimated as shown in Fig. 5. For all these scenarios, the raw ores, fluorite production, and transportation contribute little to the GWP and PED, and are neglected. For GHG emissions, the impacts of six scenarios are 100%, 85.64%, 86.90%, 70.00%, 98.77% ,and 72.03%, respectively. And for PED, the impacts of the six scenarios is 100%, 86.67%, 56.42%, 54.38, 62.06% and 58.93%, respectively.

The reason why the energy consumption of S2 is 86.67% of that of S1 is that the energy consumption of fuel production of S2 is 13.15% less than that of fuel production of S1. Due to the high thermal efficiency calcination technology based on fluidized bed, the calcination stage of the feedstock in S2 requires less heat than that in S1 and can be completely supplied by gaseous fuel. The reduction in fuel consumption directly leads to a reduction in GHG emissions during fuel combustion, as well as a reduction in GHG emissions during fuel production. As a result, the greenhouse gas emissions from fuel combustion in S2 are 11.96% less than those in S1, and the greenhouse gas emissions from fuel production in S2 are 2.31% less than those in S1. This makes GHG emissions of S1 86.67% of that of S1.

The comparison of the PED results between S3 and S2 shows that the energy consumption of the reductant production in S3 is 5.49% higher than that in S2, since the energy consumption of aluminum production is higher than that of ferrosilicon production. However, the energy consumption required for fuel production is 35.74% less than that of S2. This is due to the high reduction efficiency of aluminum as reductant, which requires less fuel to produce the same weight of the products. Thus, the total energy consumption of S3 is 30.25% less than that of S2. Compared to the GWP results of S2, the greenhouse gasses from fuel production and carbonate decomposition in S3 are 6.38% and 6.59% less than those in S2, respectively, because the efficient thermite reduction reduces not only fuel consumption but also carbonate feedstock consumption. As for the greenhouse gas emissions generated in the production of the reductant, the emission in S3 is 11.71% higher than that in S2. This is because aluminum is prepared from the electrolysis process, and the electricity is mainly generated by coal-fired power plants, which results in GHG emissions. The greenhouse gas emissions from fuel combustion in S3 are 2.52% higher than that in S2 because the carbon content of the producer gas is greater than that of the semi-coke gas, as shown in Table 2. The carbon emission of S3 is 1.26% higher than that of S2 due to the contribution of reductant and fuel combustion to the GWP of S3.

The difference in the PED results between S3 and S4 is because of the different energy consumption required for fuel production. The difference is small, only 2.04%, suggesting that the energy consumption required to produce a unit of heat value for the producer gas and the coke oven gas is similar from LCA perspective. The difference in the GWP results between S3 and S4 is caused by the difference in the greenhouse gasses emitted during fuel production and combustion. Compared to S3, carbon emissions from fuel combustion and fuel production in S4 are reduced by 12.42% and 4.48% respectively, resulting in 16.9% of the total reduction in carbon emissions. This is because the production of coke oven gas emits fewer greenhouse gasses per unit heat value than the production of producer gas, and the carbon content of coke oven gas is much smaller than that of producer gas, as shown in Table 2. It indicates that the coke oven gas is more suitable as a fuel than producer gas considering GHG emissions and PED in LCA view.

Thanks to the difference in energy consumption required for fuel production, the energy consumption of S5 is 24.61% less than that of S2. However, the GWP of S5 is 13.13% higher than that of S2. This is because the greenhouse gas emissions from fuel combustion in S5 are 15.01% more than S2, while the greenhouse gas emissions from fuel production are 1.88% less than S2. From the point of view of the LCA, the energy consumption and greenhouse gas emission of producer gas per calorific value are less than that of semi-coke gas, but the carbon content of producer gas is more than that of semi-coke gas, and therefore its carbon emissions are higher than those of semi-coke gas.

The energy consumption of S6 is only 3.13% lower than that of S5, but the carbon emissions of S6 are 26.74% lower than those of S5, due to the use of coke oven gas as fuel. The energy consumption of reductant production in S6 is 5.49% lower than that of S4, and the energy consumption of fuel production is 10.04% higher than that of S4, resulting in a 4.55% of total energy consumption increase in S6. This is because aluminum production requires higher energy consumption than ferrosilicon production, but the introduction of aluminum reductant makes the energy consumption of magnesium production per unit weight much lower than ferrosilicon reductant. In the comparison of the GWP results between S6 and S4, the GHG emissions from fuel combustion, carbonate decomposition, and fuel production in S4 are reduced by 5.32%, 6.59%, and 1.83%, respectively. However, the carbon emissions from the reductant production in S4 are increased by 11.71%, which makes the carbon emissions in S4 only 2.03% less than those in S6. This is also because a large amount of greenhouse gases are emitted during the process of aluminum production.

3.3. Economic performance

The production costs of the six scenarios are shown in Fig. 6, in which each bar represents the average value, and the error lines on each bar represent the range of the Mg ingot cost according to 25% price fluctuation of the corresponding raw materials and energy.

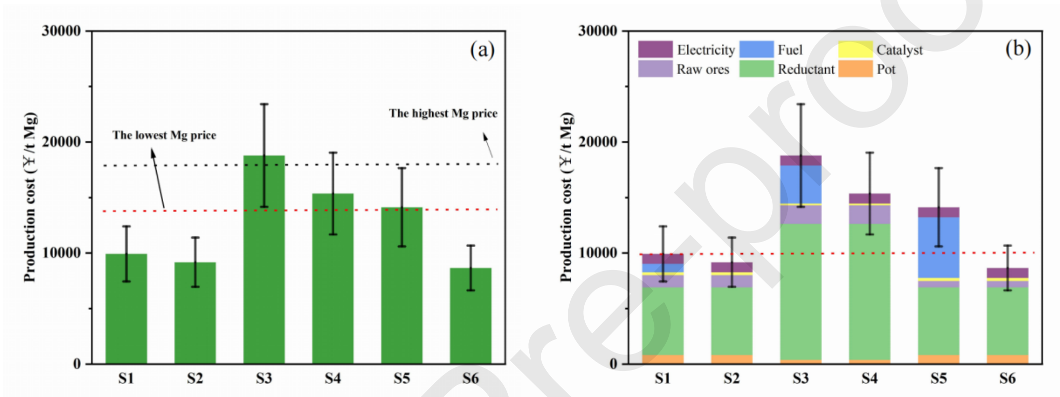

Fig. 6. Production costs of the six scenarios.

It can be seen that the average production cost ranges from about 8653 to 18790 ￥/t, with S6 being the lowest and S3 being the highest, as shown in Fig. 6(a). For S1, S2, S4, S5 and S6, the average production costs are 9925, 9175, 18790, 15360, 14126, and 8653 ￥/t, respectively. The domestic Mg ingot price fluctuates between 13,800 and 17,800 ￥/t during 2019 according to Tonhuashun finance (a Chinese financial website). It can be seen that the current raw magnesium production industry in Fugu (S1) is vulnerable to market fluctuations because of its meager profit. It indicates that only S1, S2 and S6 can be profitable and economically competitive at the lowest magnesium price.

In Fugu, a large amount of waste semi-coke gas is produced due to the concentration of the local coal chemical industry. Thus, the fuel is cheap or even free, and the fuel cost of Mg ingots can be neglected in Fugu. But in other areas, fuel costs must be taken into account if there is no cheap fuel gas. For S1, the cost of Mg ingots is primarily due to the costs associated with the reductant, the reduction pots, the electricity, raw ores, and fuel. Compared with S1, the average production cost of S2 only is reduced by about 750 ￥/t. The average cost of S3 increases about 8800 ￥/t because of the costly aluminum reductant and the extra fuel cost caused by the producer gas. The reduction in costs at S4 is mainly due to the free coke oven gas from the steelworks. Benefiting from the lower fuel costs, S4`s production cost is still considerably higher than that of S1. When aluminum is introduced as the reductant in S3 and S4, the cost of magnesium ingots rise sharply, and the average price exceeds the top of the market because of the high cost of aluminum reductant. It indicates that the reductants takes a lion's share in the cost of the aluminum process. As a result, even with free fuel, S3 and S4 are not economically competitive. When the abandoned magnesite is reused, the cost of raw ores is roughly halved. However, the average cost in S5 is still higher than in S1 and even higher than the lowest Mg price, as the cost of fuel is not negligible and offset. The process will have a price advantage when the fuel gas is freely provided, as in the case of S6. Therefore, from the economic perspective, S6 is the best choice due to its low production cost, which leads to a high economic profit.

In addition to the production costs of reduction pots, electricity, fuel, catalysts, reductants, and raw ores, the environmental cost of the environmental burden of GHG emissions is also considered in this study. The monetization of GHG emissions is achieved through the carbon trading system, so the environmental burden of greenhouse gas emissions can be directly shown in the form of economic costs. To combat climate change and global warming, some countries, including China, are establishing carbon trading systems aiming at reducing GHG emissions. The European Union Emission Trading Scheme (EUETS), which is the first multi-national emissions trading system around the world, was established by the EU in 2005 [40]. In 2011, the National Development and Reform Commission of China approved Beijing, Tianjin, Shanghai, Chongqing, Hubei, Guangdong, and Shenzhen to implement carbon emission trading pilot work (NDRC, China, 2011). Based on this pilot experience, China has begun to steadily establish a national carbon trading market since 2017 [41]. At present, China`s carbon trading market has been established and opened for trading.

Based on the trading data of the carbon market, the average cost of GHG emission is 53 ￥/t. In the EU, the trading cost is 25 €/t (that is 191 ￥/t according to 7.65 of the exchange rate). With the carbon trading costs included, the average Mg production costs are shown in Fig. 7. The GHG emission level of S1 is taken as the baseline. When a plant`s GHG emissions exceed the baseline, it have to buy an additional carbon quota. And when its emissions are below the baseline, it can sell its carbon quota.

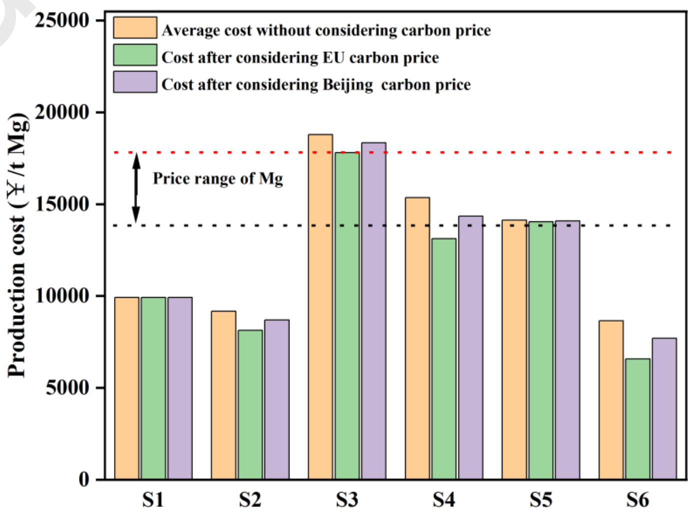

Fig. 7. Production costs of the six scenarios considering the carbon cost.

The production costs of S2, S3, S4, S5, and S6 are 8124.5, 17815.9, 13126.8, 14049.6 and 6570.7 ￥/t, respectively, considering the carbon price of the EU, and are 8696.5, 18346.3, 14341.6, 14091.2 and 7704.3 ￥/t, respectively, based on China's carbon price. It is clear that the production cost varies greatly when taking into account the cost of carbon emissions. The production costs of all the alternative processes have reduced as a result of the reduction in GHG emissions.

Note that there`s a significant cost reduction in S4 and S6 because of the great reduction in GHG emissions . It can be seen that the production cost of S5 is slightly reduced due to its limited GHG emission reduction. For S3, although it benefits from carbon trading, the production costs are still higher than the highest magnesium market price because the additional cost of reductant is not offset by the subsidies of carbon emissions reduction, even in high carbon price zone. Even using free and low carbon emissions fuel gasses, the price of S4 after the carbon subsidy is still higher than that of S2 and S6, indicating that the alumino-thermic method is not economically competitive compared to the silicon-thermic method. The carbon subsidies increases the economic competitiveness of S6, making it the cheapest option. Therefore, S6 is still the most economical option considering the environmental burden of GHG emissions.

4. Conclusion

This study evaluated the environmental and economic performance of the major prevailing metallic magnesium production processes, the Pidgeon process and five other alternative production processes through energy consumption, carbon emissions and economic characteristics in a view of life cycle. The data of energy consumption and GHG emission through the current Pidgeon process (in Fugu) are updated to 6.38×10^5 MJ and 39.3 t CO_2-eq., through fully relying on the domestic database. These data well reflected the actual level of domestic magnesium production technology and are of great significance for determining the initial carbon quota of domestic magnesium industry.

For the energy consumption of Pidgeon process, the fossil fuels (washed coal and semi-coke gas), and ferrosilicon contribute more than 95%. In descending order, the main contributions to the carbon emissions from the Pidgeon process are reductant production, fuel combustion, fuel production and carbonate decomposition. Energy conservation and emission reduction measures in the magnesium industry based on the Pidgeon process should focus on reductants and fuels.

Through the carbon trading markets in Europe and China, the environmental impacts of GHG emissions corresponding to the six scenarios are translated into their specific economic costs, which can be compared numerically. The evaluated case S6 has the lowest production costs, at 7704.3 and 6570.7 ￥/t, based on the Chinese and EU carbon prices, respectively. It was demonstrated that the route of magnesium production with local abandoned magnesite and the redundant coke oven gas from the steelworks and the novel calcination technology has the best economic performance with the cited comprehensive considerations.

CRediT authorship contribution statement

Xiaorui Huang: Conceptualization, Data curation, Formal analysis, Investigation, Writing. **Zifu Xu:** Validation, Investigation. **Liangliang Fu:** Validation, Data curation. **Zhennan Han:** Validation. **Kun Zhao:** Validation. **Kangjun Wang:** Conceptualization, Funding acquistion. **Dingrong Bai:** Writing-review & editing. **Guangwen Xu:** Writing-review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Declaration of interests

Guangwen Xu is an editor-in-chief for Carbon Resources Conversion and was not involved in the editorial review or the decision to publish this article. All authors declare that there are no competing interests.

Highlights

- First life cycle assessment of the current magnesium production process based native database in China.

- Life cycle assessment is used to determine the potential and viable processes in magnesium industry.
- GHG emissions from the production process are monetized through the carbon emission trading scheme.
- GHG emissions and energy consumption results of the current magnesium production process in China are updated.
- The magnesium production process based on the fluidized bed is verified the best choice for Liaoning by LCA.