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Life cycle greenhouse gas emissions of conventional and alternative steel production methods in countries dependent on energy import: A South Korean case study

Juha Lee [a,b], Gyuna Kwak [a,b], Yujin Jung [a,b], Wonjae Choi [a,b,*]

[a] Department of Mechanical and Biomedical Engineering, Ewha Womans University, 52, Ewhayeodae-gil, Seodaemun-gu, Seoul 03760, Korea
[b] System Health & Engineering, Ewha Womans University, 52, Ewhayeodae-gil, Seodaemun-gu, Seoul 03760, Korea

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ABSTRACT

This study used a life cycle assessment to quantitatively compare greenhouse gas emissions among traditional coal blast furnaces and alternative methods such as hydrogen direct reduction, natural gas direct reduction, and electric arc furnaces. Greenhouse gas (GHG) emissions were calculated throughout the life cycle of producing 1 ton of liquid steel (tLS) in countries dependent on energy imports through maritime transportation. The life cycle assessment results for these countries differs from those of countries capable of land-based transportation. In particular, when transporting gaseous fuels such as natural gas and hydrogen via maritime routes, liquefaction process emits a substantial GHG emissions, ultimately leading to higher life cycle GHG emissions in steel production. Therefore, this study conducted a case study on South Korea, a representative steel-producing country that relies on maritime transportation for energy imports. The analysis employed the GREET program developed by the Argonne National Laboratory in the United States, modified and expanded to reflect the Korean context. The data used in the analysis was selected through a literature review and thermodynamic modeling of the process. The life cycle assessment revealed that, coal blast furnaces emit 1612 kg-CO_2-eq./tLS, natural gas direct reduction emits 1435 kg-CO_2-eq./tLS, hydrogen direct reduction using domestically produced blue hydrogen emits 961 kg-CO_2-eq./tLS, and electric arc furnaces emit 370 kg-CO_2-eq./tLS. The electric arc furnace method, which utilizes steel scrap, emits the fewest greenhouse gases as it doesn't need the reduction process. Depending on the method of hydrogen production, the values for hydrogen direct reduction of iron ranged from 741 kg-CO_2-eq./tLS to 2352 kg-CO_2-eq./tLS, highlighting the significant impact of hydrogen production methods on the results. The variation in the life cycle of greenhouse gas emissions throughout the process was substantial depending on the electricity production method employed. Excluding coal blast furnaces, which utilizes minimal electricity externally supplied, it was observed that natural gas direct reduction, hydrogen direct reduction, and electric arc furnaces are significantly influenced by the electricity production method. When natural gas direct reduction utilizes coal-based power compared to renewable energy, it emits 2 times more the life cycle of greenhouse gas emissions. Hydrogen direct reduction uses coal-based power compared to renewable power emits 3.2 times more. Furthermore, sensitivity analysis was conducted on variables used in each steelmaking method. Confirmed was a variance in results of up to 4.5 % due to a 5 % fluctuation in the consumption of primary fuels such as coal, hydrogen, natural gas, and electricity. The other factors, excluding energy consumption exerted minimal influence, with variations below 0.5 %. The validity of energy consumption was confirmed to be appropriate based on literature and theoretical calculations used in this study. This suggests that the findings of this study are robust.

1. Introduction

The international community recognizes the seriousness of climate

* Corresponding author at: Department of Mechanical and Biomedical Engineering, Ewha Womans University, 52, Ewhayeodae-gil, Seodaemun-gu, Seoul 03760, Korea.
E-mail address: wj_choi@ewha.ac.kr (W. Choi).

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Nomenclature

LCA	Life cycle assessment
GHG	Greenhouse gas
CBAM	Carbon Border Adjustment Mechanism
CO_2	Carbon dioxide
CH_4	Methane
N_2O	Nitrous oxide
CO	Carbon monoxide
H2	Hydrogen
ST	Steam turbine
SMR	Steam methane reforming
tLS	ton of liquid steel
DRI	Direct reduced iron
WWS	Wind water and sunlight
EAF	Electric arc furnace
NG	Natural gas
NGDR	Natural gas direct reduction
NG CC	Natural gas combined cycle
H2DR	Hydrogen direct reduction

change and considers addressing climate change on a global scale the most urgent. Various countries worldwide, including the United States, those in the European Union, and China, have declared their commitment to achieving carbon neutrality by 2050, limiting the rise in global temperature to 1.5 °C to combat climate change [1].

The steel industry has high greenhouse gas emissions, accounting for more than 7 % of global CO_2 emissions [2]. The conventional method of steelmaking, primarily using coal-based blast furnaces, generates significant amounts of CO_2 emissions due to the use of coal in the iron ore reduction process. Therefore, there has been considerable interest in alternative steelmaking methods to reduce greenhouse gas emissions by using alternative fuels instead of coal for iron ore reduction.

The Carbon Border Adjustment Mechanism (CBAM) is a system proposed by the EU that evaluates the carbon emissions of products imported from countries outside the EU and imposes taxes or fees on the amount [3]. The transition period for CBAM began in October 2023 and targets six industries: Cement, electricity, fertilizers, steel, aluminum, and hydrogen. There is a need for quantitative analysis of greenhouse gas emissions from steelmaking methods that can reduce greenhouse gases.

Various attempts are being made to reduce greenhouse gas emissions in the steelmaking process. However, there is a lack of quantitative research on how much greenhouse gas each alternative emits. To determine whether alternative steelmaking methods are environmentally preferable to conventional method, it is necessary to analyze the life cycle greenhouse gas emissions produced by each steelmaking method.

To achieve the goal of producing environmentally friendly steel products, the Swedish steel company SSAB, the mining company LKAB, and the power company Vattenfall have established a joint venture called HYBRIT. The HYBRIT project aims to produce steel using hydrogen instead of fossil fuels to create eco-friendly steel products [4]. The HYBRIT project utilizes green hydrogen to reduce iron ore and produce direct reduced iron (DRI), which is melted using electricity from renewable sources to produce carbon-free steel. Additionally, various studies have been conducted on hydrogen direct reduction. Li, S. et al. [5] analyzed a method for reducing CO_2 emissions through a process that directly reduces iron ore powder using hydrogen.

Similar to hydrogen reduction steelmaking, natural gas reduction steelmaking utilizes natural gases to produce hydrogen and carbon monoxide for iron ore reduction. MIDREX is a company that produces steel using a natural gas reduction process, where natural gas is reformed to produce a reducing gas containing H_2 and CO as the reducing agents [6]. Utilizing natural gas for reduction significantly improves air quality by reducing greenhouse gas emissions compared to conventional methods.

Electric arc furnaces have the advantage of recycling scrap iron and does not need to reduce iron ore using steel scrap, which already has the form of iron. An electric arc furnace emits fewer greenhouse gases during the steelmaking process as it doesn't need the reduction process. According to the World Steel Association, electric arc furnaces using steel scraps play a crucial role in reducing greenhouse gas emissions and resource consumption. For every ton of scrap utilized, it reduces the consumption of 1.4 tons of iron ore, 740 kg of coal, and 120 kg of limestone, while reducing emissions of 1.5 tons of CO_2 [7].

This study aims to quantitatively and comparatively analyze hydrogen direct reduction steelmaking, natural gas direct reduction steelmaking, and electric arc furnace steelmaking compared to conventional steelmaking methods through a life cycle assessment of the steel production process.

Fig. 1 illustrates the four steelmaking methods to be addressed in this study. Coal blast furnace involves the iron ore undergoing sintering and the coking coal undergoing coking. Subsequently, reduction and melting of iron ore occur simultaneously in the blast furnace, resulting in the production of molten iron. After entering the basic oxygen furnace, component adjustment occurs, leading to the production of liquid steel. Hydrogen direct reduction involves pelletizing iron ore and passing it through a reduction furnace within the steel mill. Hydrogen and electricity are utilized during reduction. The direct reduced iron (DRI) obtained after passing through the reduction furnace is converted into liquid steel through an electric furnace. Natural gas direct reduction is performed similarly to hydrogen direct reduction. Instead of hydrogen, natural gas is reformed in a reformer to produce syngas containing hydrogen and carbon monoxide, which is then utilized in the reduction furnace. The electric furnace melts steel scraps to produce liquid steel, utilizing electricity and coal.

A few life cycle analyses of steel production have been conducted. Burchart-Korol, D [8] conducted a life cycle assessment of coal blast furnace and electric arc furnaces in Poland. Renzulli, P.A. [9] performed a life cycle analysis of a coal blast furnace in Italy. Yang, L. et al. [10], Hu, J.Y. et al. [11], Ma, X. et al. [12] conducted a life cycle analysis of iron production in China. These papers mainly analyze the greenhouse gas emissions generated from coal blast furnace steelmaking and electric arc furnace steelmaking in each country.

Previous papers have also presented life cycle analyses of reduction steelmaking. Nduagu, E.I. et al. [13] compared three reduction steelmaking methods: Rotary kiln DRI, Coal gasifier DRI, and natural gas reformer DRI. Fischedick, M. et al. [14], Otto, A. et al. [15], Vogl, V. et al. [16], and Bhaskar, A. et al. [17] conducted a life cycle analysis of hydrogen direct reduction. However, the results vary across these papers, and there are differences in the analytical methods employed.

Unlike the countries examined in previous studies, including Europe, China, and India, South Korea doesn't produce primary energy source and heavily rely on energy imports only through maritime transportation. Due to the marine transportation of fuels, the results of life cycle assessments for fuels such as hydrogen, natural gas, and coal inevitably vary among these countries. For natural gas and hydrogen, liquefaction should be conducted overseas before being transported via maritime routes. This fact affects the life cycle greenhouse gas emissions of fuels. Consequently, the analysis results on the whole process in countries like South Korea differ significantly from those previously studied. The results of studies can be utilized for other countries in similar situations such as Japan and Taiwan, which relies heavily on energy imports and can only import fuel through maritime transportation. However, there has been no study that has compared conventional and alternative steelmaking technologies in such countries.

To address this research gap, this study conducted life cycle assessment of conventional and alternative steelmaking technologies in such

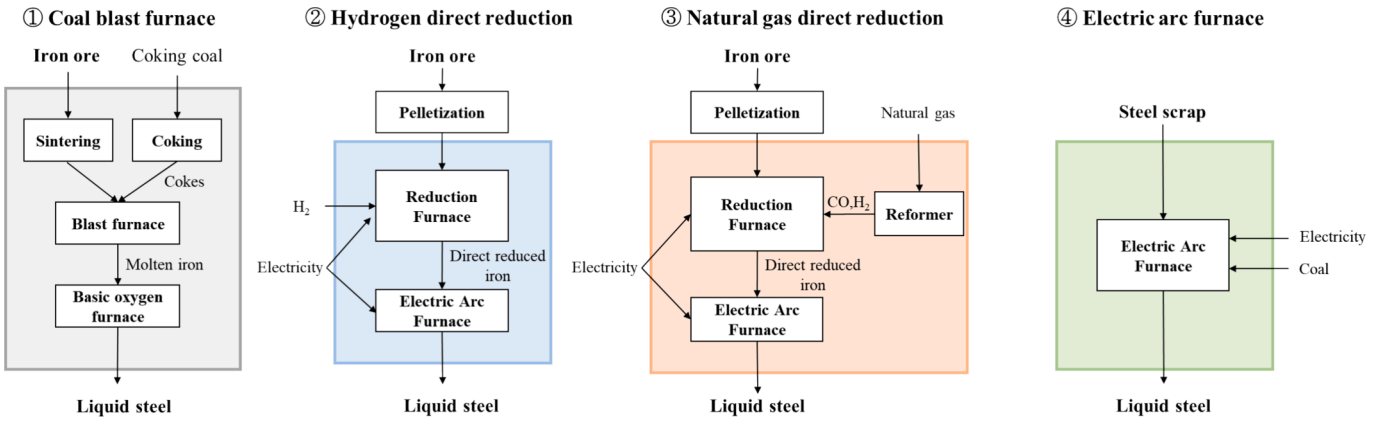


Fig.1. Schematic of steel making methods.

countries. South Korea was selected as a target region because it is one of the major steel-producing countries which actively pursue the development of alternative steelmaking technologies. South Korea ranks sixth globally in steel production, and due to the annual increase in steel production volume, greenhouse gas emissions are anticipated to increase further [18]. South Korea accounts for 12 % of global steel exports and is a country that produces and exports vast amounts of steel [19]. Therefore, the Korean steel industry must accurately understand greenhouse gas emissions from existing steel productions. POSCO, one of the world's most competitive steelmaking company headquartered in South Korea [20], is developing HYREX, a hydrogen direct reduction steelmaking process that relies on 100 % hydrogen. The South Korean government has proposed transitioning entirely from blast furnaces to electric arc furnaces and introducing hydrogen reduction steelmaking as a key mitigation measure for achieving carbon neutrality in the steel industry [21].

In contrast to the previous studies, this study aims not only to analyze a single technology but also to quantitatively compare the life cycle of greenhouse gas emissions of the conventional coal blast furnaces with three alternative steelmaking methods, which are hydrogen direct reduction, natural gas direct reduction, and electric arc furnace. Additionally, electricity and hydrogen production methods are considered in the analysis, with the intention of analyzing the combination of environmentally friendly steelmaking methods and fuel production methods.

This study aims to evaluate the life cycle of greenhouse gas emissions generated when producing 1 ton of liquid steel through four different steelmaking methods according to the electricity generation and hydrogen production methods. To achieve this goal, the manuscript is composed as follows. Firstly, in Section 2, the scope involved in producing liquid steel for each steelmaking method was defined. Subsequently, data collection and modeling calculated the energy required for each process. This study modeled reduction and electric arc furnaces using the same thermodynamic framework to compare the four steelmaking methods on an equal mechanism. This content will be addressed in Section 2.3. Using these data, the greenhouse gas emissions generated in each process were calculated, and the life cycle of greenhouse gas emissions was determined according to the steelmaking method. In addition, in Section 4.1, an analysis of the life cycle process of steel production considering electricity and hydrogen production methods was conducted to analyze how electricity and hydrogen produced could be more environmentally friendly than conventional coal blast furnace steel production. Finally, in Section 4.2, sensitivity analysis verified the changes in the life cycle of greenhouse gas emissions according to variations in the energy used.

2. Methodology

2.1. Scope and framework

This study compares the life cycle of greenhouse gas emissions from liquid steel produced through four different steel production methods. Liquid steel refers to the product after the composition adjustment of molten iron ore and before undergoing continuous casting and rolling processes. Greenhouse gas emissions include CO_2, CH_4, and N_2O. This study used Global Warming Potential values of 1, 29.8, and 273 for CO_2, CH_4, and N_2O, respectively [22]. The functional unit is 1 ton of liquid steel. Only the greenhouse gas emissions from the process of producing liquid steel from raw materials were considered in the calculations, excluding emissions from constructing facilities such as blast furnaces and electric arc furnaces.

The GREET program, developed by the U.S. Argonne National Laboratory, was utilized in this study. In our previous study [23], the GREET program was extended and modified to suit the South Korean situation. Table 1 shows the life cycle GHG emissions per 1 GJ of fuel from the previous study.

Greenhouse gas emissions for electricity and hydrogen vary depending on their production methods. Table 2 presents the life cycle of GHG emissions for electricity and hydrogen according to their production methods. The upstream process in Table 2 includes processes such as the extraction and import of raw materials used in electricity and hydrogen production. The life cycle of greenhouse gas emissions from electricity were calculated using data from the Korea Electric Power Corporation for the year 2022 [24,25]. It was assumed that hydrogen is compressed to 3 MPa at the production site and transported to the steel mill, in accordance with the domestic Clean Hydrogen Certification System. Despite ongoing debates about the cleanliness of blue hydrogen, the life cycle greenhouse gas emissions of hydrogen were calculated based on the GREET model developed by the reputable Argonne National Laboratory [26]. It is noted that the value for domestic blue hydrogen was referenced from our previous study [27]. Detailed hydrogen analysis, including imported hydrogen, is provided in Supplementary S1.

Table 1
The life cycle of GHG fuel emissions in South Korea (g-CO_2-eq./GJ) [23].

Fuel	Upstream (g-CO_2-eq./GJ)	Fuel use (g-CO_2-eq./GJ)
Coal	6160	87,627
Natural gas	15,384	55,106
Diesel	11,583	75,171
LPG	12,151	67,388
Residual oil	9137	80,474

Table 2
The life cycle of GHG emissions for electricity and hydrogen according to production technology.

		Upstream process	Power generation	Hydrogen production	Total
Electricity	South Korea avg. [24,25]	66.859	470.642	0	537.502
(g-CO_2.eq./kWh)	Coal steam turbine [24,25]	65.567	1008.061	0	1073.628
	Natural gas combined cycle [24,25]	123.091	453.787	0	576.878
	Uranium steam turbine [24,25]	8.759	0	0	8.759
	Renewable—wind, water, solar [24,25]	0	0	0	0
	By-product gas [24,25]	0	1425.460	0	1425.460
Hydrogen	Blue hydrogen[27] [1](Natural gas reforming with CCS)	1.790	0	2.717	4.507
(kg-CO_2-eq./kg)	Grey hydrogen [23][1](Natural gas reforming)	1.742	0	8.665	10.408
	Green hydrogen [23] (Electrolysis with renewable power)	0.026	0	0.410	0.436
	Electrolysis with grid electricity [23]	29.857	0	0.410	30.267
	Naphtha cracking [23]	1.266	0	1.240	2.506

[1]The emissions from the upstream process of blue hydrogen and grey hydrogen differ due to the varying amounts of natural gas used for hydrogen production and carbon capture. Natural gas is used in supplying heat for carbon capture.

2.2. Steel production Pathway

Fig. 2 shows the life cycle of four different liquid steel production methods. In a coal blast furnace, firstly, the raw material, iron ore, undergoes mining. The mined iron ore is transported to domestic steel mill. The iron ore goes through the sintering process at the sintering plant, while coal is processed in the coke oven to produce coke. The coke is used to reduce and melt the sintered iron ore in the blast furnace. The composition is adjusted after passing through the basic oxygen furnace, resulting in liquid steel.

In hydrogen direct reduction, the process begins with mining iron ore and then pelletizing it to produce iron ore pellets. The produced iron ore pellets are transported to domestic ironworks. Hydrogen is used to reduce the iron ore pellets in the reduction furnace of the ironworks. The resulting DRI is melted into liquid steel using electricity in an electric furnace.

Natural gas direct reduction follows a process similar to hydrogen direct reduction, whereby iron ore is mined and then pelletized. The produced iron ore pellets are transported to domestic ironworks. Natural gas is used for reduction in the reduction furnace of the ironworks. Subsequently, the DRI is processed in an electric furnace where electricity is used to produce liquid steel.

An electric arc furnace is a steelmaking method that differs from other steelmaking methods, which use steel scrap instead of iron ore. Initially, steel scrap is collected and undergoes preprocessing before being transported to domestic ironworks or imported. Afterward, the steel scrap is melted using electricity in the electric arc furnace located within the ironworks to produce liquid steel. To save energy in the electric furnace, coal, as a chemical energy source, is introduced to reduce the consumption of electrical energy, thus conserving energy [28,29].

The data used for each steelmaking method is summarized in Table 3.

2.3. Thermodynamic modeling

No operational data are available since hydrogen direct reduction has not been commercialized. Hence, modeling is necessary to validate the data obtained through a literature review. Hydrogen direct reduction, natural gas direct reduction, and electric arc furnace steelmaking were modeled on the same basis for comparative analysis. The modeling referenced A Bhaskar et al., *Energies*, 2020 [17]. The required energy for each process was calculated based on the chemical reactions occurring. The energy required for hydrogen direct reduction, natural gas direct reduction, and electric arc furnace steelmaking was calculated using the enthalpy difference when melting DRI and steel scrap at high

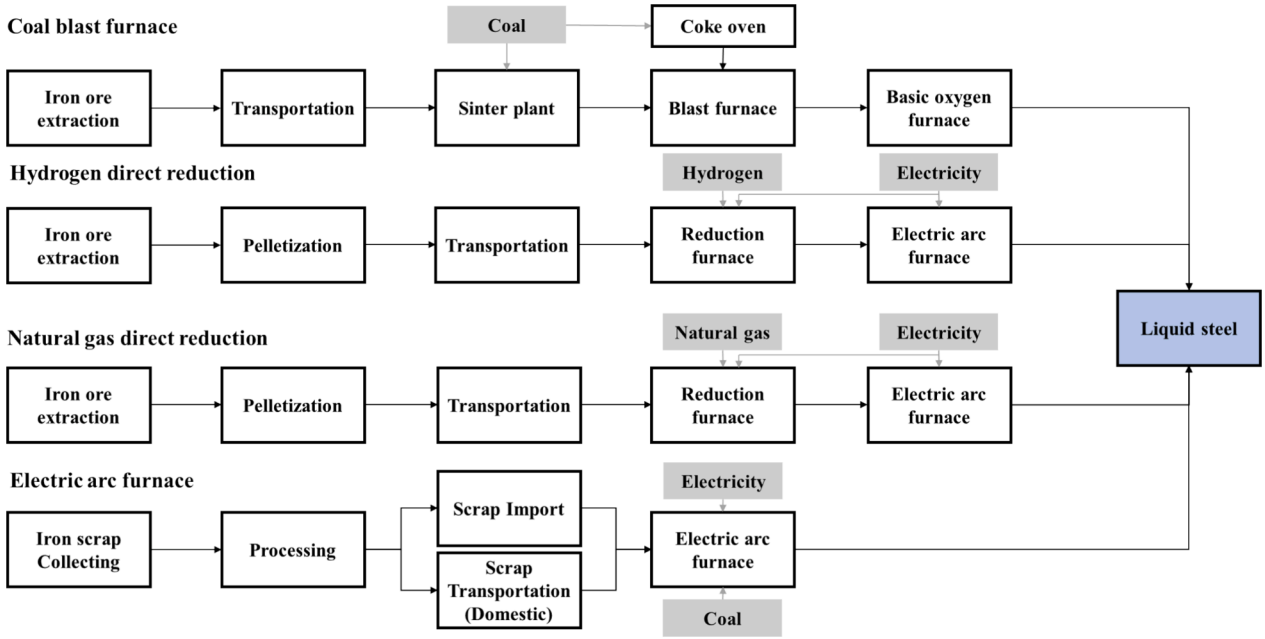


Fig.2. Liquid steel production pathways in South Korea.

Table 3
Life cycle inventory for steel production.

Steelmaking Method	Process			Unit
Coal blast furnace	**Iron ore mining**	Electricity	3.8 [30]	kWh/t-iron ore
		Diesel	3.4 [30]	kg/t-iron ore
	Transportation	Cargo payload	180,000 [31]	t
		Distance	4,009 [32]	miles
		Residual oil	100[1]	%
	Steel mill (Sinter plant, coke oven, blast furnace, and basic oxygen furnace)	Iron ore	1490.251 [33]	kg/tLS
		Coal	693.593 [33]	kg/tLS
		Electricity	10 [8,33]	kWh/tLS
		LNG	34.9 [33]	Nm^3/tLS
Hydrogen direct reduction	**Iron ore mining**	Electricity	3.8 [30]	kWh/t-iron ore
		Diesel	3.4 [30]	kg/t-iron ore
	Transportation	Cargo payload	180,000 [31]	t
		Distance	4,009 [32]	miles
		Residual oil	100 [1]	%
	Steel mill (Reduction furnace and electric arc furnace)	Iron ore	1600[2]	kg/tLS
		Electricity	946.38 [2]	kWh/tLS
		Hydrogen	54 [2]	kg/tLS
Natural gas direct reduction	**Iron ore mining**	Electricity	3.8 [30]	kWh/t-iron ore
		Diesel	3.4 [30]	kg/t-iron ore
	Transportation	Cargo payload	180,000 [31]	t
		Distance	4,009 [32]	miles
		Residual oil	100 [1]	%
	Steel mill (Reduction furnace and electric arc furnace)	Iron ore	1600 [2]	kg/tLS
		Electricity	889.63 [2]	kWh/tLS
		Natural gas	220.24[2]	kg/tLS
Electric arc furnace	**Steel scrap collecting**	Diesel	4.1[34]	L/t-iron scrap
	Steel scrap transportation			
	Prompt scrap	Distance	338[3]	km
		Diesel	19.31 [34]	L/t-iron scrap
	Obsolete scrap	Distance	140[4]	km
		Diesel	10.4 [34]	L/t-iron scrap
	Imported scrap	Cargo payload	20,000 [35]	t
		Distance	1,169 [32]	miles
		Residual oil	100 [1]	%
	Steel scrap processing (of obsolete scrap and Imported scrap)	LPG	0.35 [36]	kg/tLS
		Diesel	21.77 [36]	kg/tLS
		Electricity	33.83 [36]	kWh/tLS
	Steel mill (Electric arc furnace)	Steel scrap	1212.05 [8,37]	kg/tLS
		Electricity	400 [2]	kWh/tLS
		Coal	241 [2]	kWh/tLS

[1]Value was assumed for the analysis.
[2]Values determined through the modeling and simulation from this study.
[3]The distance from Hyundai Motor's Ulsan plant to Hyundai Steel's Dangjin steel mill.
[4]The distance from Yangju City, Gyeonggi-do Province, to Hyundai Steel's Dangjin steel mill.

temperatures. The schematic of direct reduction and electric arc furnaces is shown in Fig. 3.

The modeling of hydrogen direct reduction was structured using the following methodology. Firstly, pellets at 25 °C are heated to the operating temperature of the reduction furnace, which is 800 °C, before being introduced into the furnace. The energy required for pellet heating was calculated based on the enthalpy difference depending on the temperature of the iron ore. The energy was assumed to be supplied by electricity. Then, the heated pellets were modeled to enter the reduction furnace, with the operating temperature of the furnace set at 800 °C. In the case of hydrogen direct reduction, the reduction furnace operates at a lower temperature than natural gas direct reduction; hydrogen direct reduction operates at temperatures below 900 °C. Pure hydrogen has a higher reduction rate than syngas [16]. Furthermore, operating at temperatures higher than 900 °C leads to a decrease in reaction rates due to changes in the outer layer of the pellets. As a result, the furnace mainly operates at temperatures around 800 °C, where phase transformations of iron occur. Equation (3) describes the chemical reaction in the reduction furnace [14].

$$Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O \quad (1)$$

At 800 °C, pellets react with hydrogen entering at 500 °C to produce Fe and H_2O. Therefore, the amount of energy required in the reduction furnace is calculated using the enthalpy difference in Eq. (1). The energy is also supplied by electricity. The waste stream exiting the reduction furnace is water, and the temperature of the waste stream decreases from the furnace operating temperature of 800 °C to 25 °C. It is assumed that heat exchange is performed to allow the hydrogen entering the furnace at 25 °C to reach 500 °C [17]. Subsequently, the DRI exiting the reduction furnace is modeled to enter an electric arc furnace operating at a temperature higher than the melting point of iron, specifically 1650 °C. Considering the heat loss occurring when DRI moves from the reduction furnace to the electric furnace, it is assumed that 700 °C DRI enters the electric furnace and turns into 1650 °C liquid steel. The energy used in the electric arc furnace is also calculated using the enthalpy difference based on the temperature of the iron. The liquid steel exiting the reduction and electric arc furnaces is set to be 100 % Fe. The electrical heating efficiency during pellet heating is assumed to be 0.85, and the efficiency of the electric arc furnace is considered to be 0.6 for the calculations.

The reduction furnace and electric furnace for natural gas direct reduction were also modeled to determine the required amount of fuel. As depicted in Fig. 3, modeling was conducted to enable comparison with hydrogen direct reduction. Pellets were heated from 25 °C to the operating temperature of the shaft reduction furnace, which is 980 °C, and then introduced into the shaft reduction furnace. Natural gas direct reduction is reduced at a higher temperature than hydrogen direct reduction. Suppose a small amount of CO is added to the reduction gas compared to pure hydrogen. In that case, adding CO decreases the diffusivity of the reduction gas, slowing down the reduction reaction [38]. Additionally, since syngas passes through, the natural gas reformer exits at 980 °C, the operating temperature of the reduction furnace was set at 980 °C for modeling [39]. The outlet stream from the reduction furnace consists of H_2O and CO_2 and undergoes heat exchange as it decreases from 980 °C to 25 °C, assuming that the natural gas passes through a reformer before entering the reduction furnace as the inlet stream. The efficiency of heat exchange is assumed to be 0.85. It was assumed that the energy shortfall required by the reformer is supplied by natural gas after supplying the outlet stream. Subsequently, considering the heat loss, the 880 °C DRI exiting the reduction furnace is modeled to enter an electric furnace operating at 1650 °C. Similar to hydrogen direct reduction, the composition and efficiency of the liquid steel were

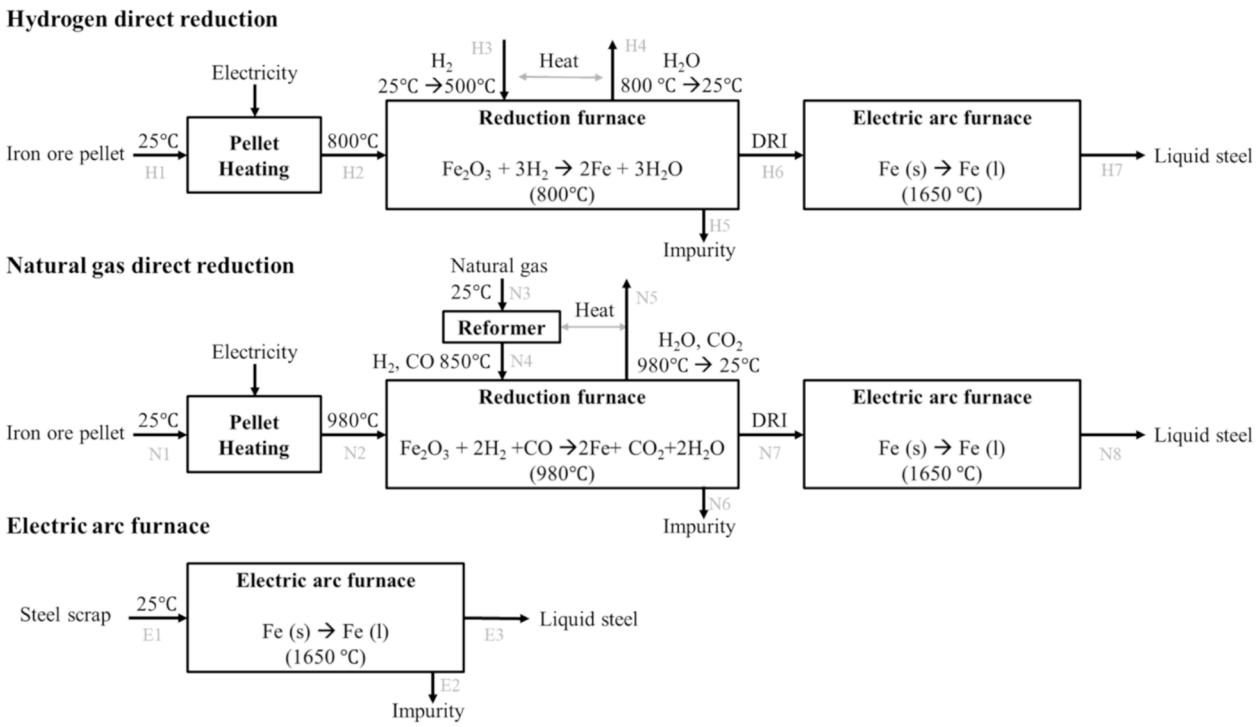


Fig.3. Schematic of direct reduction and electric arc furnaces.

considered in the calculations.

The energy used when utilizing an electric furnace in the steel mill is also modeled as shown in Fig. 3. It is assumed that steel scrap at 25 °C is melted in the electric furnace operating at 1650 °C, and similar to other steelmaking methods, the composition of the liquid steel exiting the electric furnace is assumed to be 100 % Fe.

The mass and energy flows used for modeling hydrogen direct reduction, natural gas direct reduction, and electric arc furnace are presented in Table 4. Table 4 was constructed based on the stream numbers indicated in the schematic diagram of the modeling shown in Fig. 3. In this modeling, the reduction furnace calculations were performed by considering the mole flow rates of each stream. Additionally, the mass balance was adjusted by accounting for the amount of impurities generated during the reduction furnace process.

3. Life cycle assessment

The life cycle GHG emissions of liquid steel produced by each steelmaking method were calculated using the data from Tables 1–3.

3.1. Coal blast furnace

Steel production using blast furnaces is currently the most widely used steelmaking method. Iron ore reduction and melting occur simultaneously inside the blast furnace, and coal is used as fuel during this process.

Iron ore mining.

South Korea imports iron ore from various countries. The import quantities of iron ore from each country, in 2021, are provided in Supplementary Table S2 [40], which shows that Australia accounts for the largest proportion. To reduce the complexity of analysis, this study assumes that the iron ore was mined in Australia. During the mining of 1 ton of iron ore, 3.4 kg of diesel and 3.8 kWh of electricity are used in Australia [30]. The life cycle GHG emissions of Australian electricity were calculated using the 2021 electricity generation ratios published by the Australian government [41,42]. The generation mix of Australia is provided in Supplementary Tables S3–S4. Values such as power generation efficiency, except for the generation mix, utilize the default parameters provided by the GREET 2022 model. The life cycle GHG emissions of diesel were assumed to be the same as the existing values in GREET 2022. The greenhouse gas emissions per 1 GJ of Australian electricity and diesel used in the calculations are listed in Supplementary Table S5.

Table 4
Mass and energy flow of modeling.

Steelmaking Method	Stream	Temperature (°C)	Mass Flow (kg/tLS)	Enthalpy (kJ/kg)	Short Description
Hydrogen direct reduction	H1	25	1600	−825.5	Iron ore pellets
	H2	800	1600	−146.5	Heated iron ore pellets
	H3	500	54	6897	H_2 heating
	H4	800	484	1613	H_2O from waste stream
	H5	–	107	–	Impurity
	H6	700	1063	315	DRI
	H7	1650	1000	909	Liquid steel
Natural gas direct reduction	N1	25	1600	−825.5	Iron ore pellets
	N2	980	1600	30.5	Heated iron ore pellets
	N3	25	220	312	Natural gas entering the reformer
	N4	850	220	615	H_2, CO from reformer
	N5	980	658	−1018	H_2O, CO_2 from waste stream
	N6	–	99	–	Impurity
	N7	880	1063	450	DRI
	N8	1650	1000	909	Liquid steel
Electric arc furnace	E1	25	1212	0	Steel scraps
	E2	–	212	–	Impurity
	E3	1650	1000	909	Liquid steel

Using these values for the calculation, the greenhouse gas emissions of mining process are calculated at 20 kg-CO_2-eq./tLS. For the reference, Supplementary Table S6 provides a comparison between the theoretically required amount of iron ore in a coal blast furnace and the values from the reference literature.

Iron ore transportation

The iron ore is assumed to be transported from Australia's Hedland Port to Pohang, South Korea, where POSCO is located. The maritime distance for this route is 3484 nautical miles, equivalent to 4009 miles [32,43]. It is assumed that each vessel transports 180,000 tons of iron ore using residual oil-powered ocean tankers [31]. Detailed procedures for calculating total emissions during transportation by ocean tanker are provided in Supplementary Fig. S1 and Supplementary Table S7. The greenhouse gas emission from this process is 32 kg-CO_2-eq./tLS.

Process in the steel mill (sintering and coke oven and blast furnacing and basic oxygen furnacing).

This study calculated greenhouse gas emissions from various processes (sintering, coking, blast furnace, and converter) in the steelmaking process using activity data from POSCO, a South Korean company [33]. According to POSCO, 34.9 Nm^3 of LNG, 694 kg of coal, and 60 kWh of electricity produces 1 ton of steel products. Excluding the electricity used in the continuous casting and rolling processes, this study assumes that 10 kWh of electricity is used to produce 1ton of liquid steel [8]. Additionally, produce 1 ton of liquid steel in the steelmaking process. The greenhouse gas emissions from the steelmaking process amount to 1560 kg-CO_2-eq./tLS. Therefore, the life cycle greenhouse gas emissions from the entire process of the coal blast furnace are 1612 kg-CO_2-eq./tLS.

3.2. Hydrogen direct reduction

Hydrogen direct reduction steelmaking is a reduction method that utilizes hydrogen as the reducing agent. In this process, iron ore is reduced using hydrogen instead of CO gas, traditionally used as the reducing agent in conventional blast furnace methods. The reduction reactions for coal-based blast furnace steelmaking and hydrogen direct reduction steelmaking are indicated by Eqs. (2)–(3).

$$Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2 \quad (2)$$

$$Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O \quad (3)$$

Coal blast furnaces generate CO_2, while hydrogen direct reduction steelmaking produces H_2O, making it a steelmaking method with lower carbon emissions than traditional methods. This aspect has garnered attention.

Iron ore mining.

In hydrogen direct reduction steelmaking, steel production is primarily carried out using hematite pellets. Unlike the sintered ore used in coal-based blast furnace steelmaking, hydrogen direct reduction steelmaking employs hematite because it undergoes reduction by hydrogen at higher temperatures more rapidly than magnetite [44]. While hydrogen direct reduction steelmaking utilizes hematite, this study calculated the mining of iron ore for hydrogen direct reduction steelmaking using the same method as in 3.1.

The amount of iron ore required for hydrogen reduction steelmaking was also determined through modeling and compared to theoretically required values, summarized in Supplementary Table S8. A metallization rate of 0.94 was set in the modeling [17]. Metallization refers to the proportion of metallic iron compared to the total iron content. It was assumed that hematite accounted for 95 % of the mined iron ore. The mined iron ore was assumed to contain 3 % SiO_2 and 2 % Al_2O_3, and the modeling results showed that 1600 kg of iron ore is needed to produce 1 ton of liquid steel. Therefore, the greenhouse gas emissions from iron ore mining for hydrogen direct reduction are 21 kg-CO_2-eq./tLS.

Pelletization

Pelletization is a process of crushing low-grade iron ore to a certain grade and then re-agglomerating it. Pelletization is similar to the sintering process in coal-based steelmaking. In direct reduction steelmaking, since reducing gas must pass through the iron ores in the shaft reduction furnace, iron ores of a certain size and shape, typically spherical, are utilized [45]. Unlike the sintering process, pelletization involves shaping iron ore into uniform-sized pellets. In the pelletization process, a 698.9 MJ/ton pellet of coal and a 94.5 MJ/ton pellet of electricity are used [46]. In order to evaluate the sensitivity of these parameters, in Section 4.2, a sensitivity analysis was conducted.

The life cycle greenhouse gas emissions of the fuel used in pelletization was based on values from Australia because pelletization typically occurs near the mined ore site. The greenhouse gas emissions during the pelletization process amount to 153 kg-CO2-eq./tLS.

Iron pellet transportation

Iron pellet transportation assumes the use of the same vessel for importing iron ore across all processes, resulting in the same cargo payload value, which was calculated in the same manner as in 3.1. Considering the amount of iron ore required to produce 1 ton of liquid steel through hydrogen direct reduction steelmaking, the amount of 35 kg-CO2-eq./tLS is generated.

Process in the steel mill (reduction furnacing and electric arc furnacing).

According to the results of model in Section 2.3, 387 kWh of energy is used for pellet heating, 159 kWh for reduction, and 400 kWh in the electric arc furnace. The heat discarded in the outlet stream contains sufficient energy to heat hydrogen; thus, no additional energy is needed for hydrogen heating. Therefore, the total electricity required for the reduction and electric furnaces is 946 kWh. Additionally, the amount of hydrogen required to produce 1 ton of liquid steel is calculated to be 54 kg. The results obtained through modeling were comparable to those obtained through literature review, as shown in Supplementary Table S9 [4,14–17].

In hydrogen direct reduction, the used hydrogen is produced in Korea from natural gas reforming with CCS, commonly known as blue hydrogen. According to the analysis, the greenhouse gas emissions from the reduction furnace and electric furnace in the hydrogen direct reduction plant amounted to 752 kg-CO2-eq./tLS, with the total greenhouse gas emissions from the life cycle of hydrogen direct reduction being 961 kg-CO2-eq./tLS.

3.3. Natural gas direct reduction

In natural gas direct reduction steelmaking, natural gas is modified as a reducing agent to contain approximately 55 % hydrogen. The reduction reaction in natural gas direct reduction steelmaking is expressed by Eq. (4).

$$Fe_2O_3 + 2H_2 + CO \rightarrow 2Fe + CO_2 + 2H_2O \quad (4)$$

Iron ore mining.

Iron ore mining for natural gas direct reduction steelmaking was also assessed using the same method as in 3.1 to determine the GHG emissions of the iron ore mining process. Therefore, the GHG emissions from the iron ore mining process for natural gas direct reduction steelmaking are 21 kg-CO2-eq./tLS.

Pelletization

Iron ore pellets are also utilized in natural gas direct reduction steelmaking. Calculations were conducted using the same method as in 3.2. Therefore, considering the iron ore required to produce 1 ton of liquid steel through natural gas direct reduction steelmaking, the greenhouse gas emissions from the pelletization process amount to 153 kg-CO2-eq./tLS.

Iron pellet transportation

Iron pellet transportation assumes the use of the same vessel for importing iron ore across all processes, resulting in the same cargo payload value, which was calculated in the same manner as in 3.1.

Considering the amount of iron ore required to produce 1 ton of liquid steel through natural gas direct reduction, emissions of 35 kg-CO2-eq./tLS occur.

Process in the steel mill (reduction furnacing and electric arc furnacing).

The transported iron ore pellets undergo a reduction process in the shaft reduction furnace. The DRI produced in the shaft reduction furnace is then melted in an electric furnace to become liquid steel.

According to the modeling results, 476 kWh of energy is used for pellet heating, 103 kWh for reduction, and 311 kWh in the electric furnace. The energy emitted from the outlet stream is 295 kWh, while the energy required by the natural gas reformer is 682 kWh. Considering the heat exchange efficiency, the energy required by the reformer after heat exchange is 431 kWh, equivalent to 32 kg of natural gas. Additionally, the amount of natural gas needed to produce 1 ton of liquid steel is calculated as 188 kg.

Therefore, the total electricity required for the reduction and electric furnaces is 890 kWh. The total natural gas required is 220 kg. The modeling of natural gas direct reduction also yielded energy requirements within the steel mill that were comparable to values obtained in the literature, as summarized and compared in Supplementary Table S10 [13,38,39,47].

The greenhouse gas emissions from the reduction furnace and electric furnace of the natural gas direct reduction steelmaking plant amount to 1226 kg-CO2-eq./tLS, and the total greenhouse gas emissions from the entire process of natural gas direct reduction steelmaking are 1435 kg-CO2-eq./tLS.

3.4. Electric arc furnace

Unlike the preceeding methods, the electric arc furnace method does not use iron ore but instead utilizes steel scrap. Steel scrap is obtained from discarded iron materials such as scrapped vehicles and ships, which can be recycled without requiring reduction. This aspect offers the advantage of further reducing greenhouse gas emissions.

Steel scrap collecting.

Fig. 4 shows steel scrap classifications [48]. Steel scrap is broadly categorized into domestic steel scrap and imported steel scrap.

Domestic steel scrap is divided into home and domestically purchased steel scrap. Home steel scrap refers to scrap generated in the steelmaking or iron manufacturing process. Home steel scrap is high quality and does not require additional processing or transportation, as it is generated within the steel mill.

Domestically purchased steel scrap is divided into prompt and obsolete steel scrap. Prompt steel scrap is generated while manufacturing products using steel, such as automobiles. Although prompt steel scrap undergoes transportation from the product manufacturer to the steel mill, it does not require additional processing as it has already been processed.

Obsolete scrap refers to scrap generated in the disposal process of products using steel products. Since obsolete scrap comes in various qualities and shapes, it undergoes preprocessing before use because it cannot be used as generated.

When collecting scrap, 4.1 L of diesel is used per ton of steel scrap [34]. All scrap except for home steel scrap goes through the collection process. Steel scrap collected through the collection process emits 15 kg-CO2-eq./tLS.

Scrap transportation and preprocessing.

Collected scrap steel, excluding home steel scrap, is transported to the steel mill. All iron scrap is assumed to be transported to the Dangjin steel mill of Hyundai Steel, a leading domestic steel production company, using electricity. Since home steel scrap is generated within the steel mill, transportation is not necessary.

As mentioned earlier, prompt scrap is generated during the manufacturing process of products, meaning it is transported from product manufacturing factories to steel mills. Steel scrap generated in automobile factories is assumed to be used among various steel products.

Obsolete scrap from scrapped cars is assumed to be generated among various scrap steel products. Therefore, the distance from the scrap car yards, primarily concentrated in Yangju, Gyeonggi Province, to the Hyundai Steel Dangjin Steel Mill was calculated [49].

Obsolete scrap undergoes a preprocessing stage using shredders. This involves shredding large waste materials such as automobiles or home appliances containing a significant amount of non-ferrous metals or non-metals [50]. The process then separates and recovers iron, non-ferrous metals, and dust using magnetic and gravitational forces. The ferrous metal generated during the dismantling process of one end-of-life vehicle (ELV) and the energy used are listed in Table 2.

Imported scrap is assumed to be based on the countries and quantities of steel scrap imported in 2021, according to the Korea Customs Service [40]. The countries and quantities of steel scrap imported into South Korea in 2021 are summarized in Supplementary Table S11. Since South Korea imports 64.3 % of its steel scrap from Japan, all imported steel scrap is assumed to come from Japan. Imported scrap undergoes the same scrap preprocessing process as obsolete scrap.

The life cycle of greenhouse gas emissions for each scrap type is summarized in the Supplementary Table S12. During the transportation and preprocessing of steel scrap by type, the greenhouse gas emissions were determined using the steel scrap usage ratio by type for 1 ton of steel scrap used. As of 2019, the domestic steel scrap usage ratio is the same as in Supplementary Table S13 [51]. Therefore, the greenhouse gas emission of scrap transportation and preprocessing are calculated at 74 kg-CO2-eq./tLS.

Process in the steel mill (electric arc furnacing).

As a result of modeling the electric furnace, it was found that 641 kWh/tLS of energy was required, and this similarity was verified by comparing it with actual operating data, which is presented in Supplementary Table S14 [8,52–55]. Considering that the actual operation of the electric furnace requires both electricity and chemical energy, this

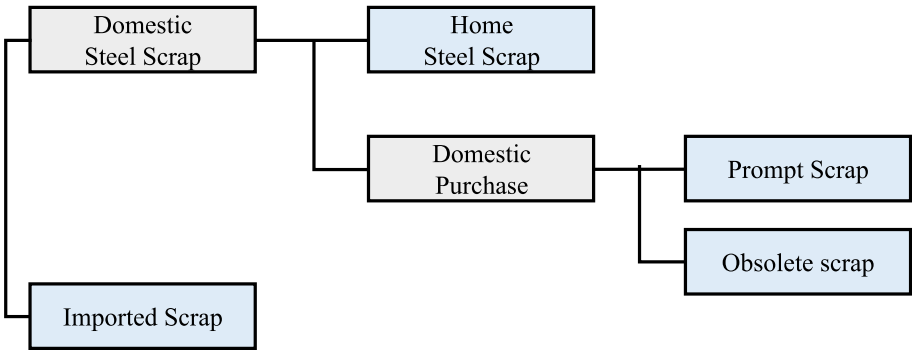


Fig.4. Steel scrap classifications.

study uses 400 kWh/tLS of electricity and 241 kWh/tLS of coal. Therefore, the greenhouse gas emissions generated during the operation of the electric furnace at the steel mill amount to 296 kg-CO2-eq./tLS, and the total greenhouse gas emissions from the entire process of electric furnace steelmaking are 370 kg-CO2-eq./tLS.

4. Results

4.1. Life cycle assessment

Fig. 5 shows the life cycle GHG emissions from four different steel production methods. In Fig. 5, electricity was assumed as the national average electricity in South Korea and hydrogen was assumed as blue hydrogen produced domestically. In Fig. 5, the greenhouse gas emissions in steel mill are divided into greenhouse gas emissions from the upstream processes of fuel use and emissions generated during combustion at the steel mill. For electricity and hydrogen, since there are no greenhouse gas emissions from combustion at the steel mill, only the upstream values are presented. Supplementary Table S15 presents detailed values of life cycle of greenhouse gas emissions from steel production.

Based on the analysis, coal blast furnaces emit the highest amount of greenhouse gases, followed by natural gas direct reduction, hydrogen direct reduction using blue hydrogen, and electric arc furnaces, in that order. This indicates that using hydrogen or natural gas in the reduction processes can reduce greenhouse gas emissions compared to traditional coal blast furnaces. Alternatively, electric arc furnaces have very low greenhouse gas emissions compared to other steelmaking methods because they only involve melting iron scrap without a reduction process.

Hydrogen direct reduction and natural gas direct reduction employ similar methods, yet a 434 kg-CO2-eq./tLS difference exists between them. The greenhouse gas emissions from the iron ore mining, transportation, and pelletization processes are the same for the natural gas and hydrogen direct reductions. Despite hydrogen direct reduction consuming more electricity, the higher life cycle of greenhouse gas emissions in the natural gas direct reduction method is due to the significant greenhouse gas emissions generated when using natural gas at the steel mill. In contrast, hydrogen emits no greenhouse gases when used at the steel mill, making steelmaking more environmentally friendly. In hydrogen direct reduction, greenhouse gas emissions from electricity usage are the largest contributing factor, and emissions from hydrogen usage are also considerable. Even when using blue hydrogen, greenhouse gas emissions from hydrogen production are still notable. While neither hydrogen nor electricity emits greenhouse gases when used at the steel mill, significant greenhouse gas emissions occur during production. Therefore, it is crucial to consider how hydrogen or electricity is produced, and a life cycle assessment based on hydrogen and electricity production methods is essential.

Fig. 6 shows the life cycle GHG emissions of four steel production methods according to life cycle GHG emissions of electricity. The detailed values utilized in Fig. 6 are summarized in Supplementary Table S16. It can be observed that the case of coal blast furnace does not change significantly due to its low consumption of electricity externally supplied. However, hydrogen direct reduction, natural gas direct reduction, and electric arc furnaces, which consume a considerable amount of electricity, exhibit significant variations in greenhouse gas emissions depending on the electricity production method. Due to the significantly higher quantity of electricity utilized in the hydrogen direct reduction and natural gas direct reduction compared to that in electric arc furnaces, the graph of electric arc furnaces exhibits a relatively less inclined.

Notably, the use of electricity generated from by-product gas, which is generated in large quantities from the conventional steel mills, for hydrogen direct reduction results in 12 % more greenhouse gas emissions than coal blast furnaces. For natural gas direct reduction, greenhouse gas emissions are higher when using electricity produced from coal steam turbine power generation or by-product gas power generation compared to coal blast furnaces. Conversely, hydrogen direct reduction utilizing electricity generated from renewable energy results in lower greenhouse gas emissions at 452 kg-CO2-eq./tLS. The electric arc furnace method exhibits relatively low greenhouse gas emissions regardless of the electricity production method, emitting 155 kg-CO2-eq./tLS when renewable energy is used. These emissions are attributed to the energy used for collecting, preprocessing, and transporting steel scrap and the portion of coal used in the electric furnace.

Fig. 7 shows the life cycle GHG emissions of four steel production methods according to life cycle GHG emissions of hydrogen. In the figure, green, blue, and grey hydrogen indicate the hydrogen produced domestically from electrolysis with renewable power, natural gas reforming with CCS, and natural gas reforming, respectively. Additionally, for comparison with imported hydrogen, a supplementary analysis was conducted on green hydrogen and blue hydrogen production in Australia, considering two import scenarios: as ammonia and as liquefied hydrogen. The results are presented in Fig. 7. The life cycle of greenhouse gas emissions of electricity is assumed to be the average electricity value in South Korea. Supplementary Table S17 presents detailed values of Fig. 7. Hydrogen direct reduction using electrolysis

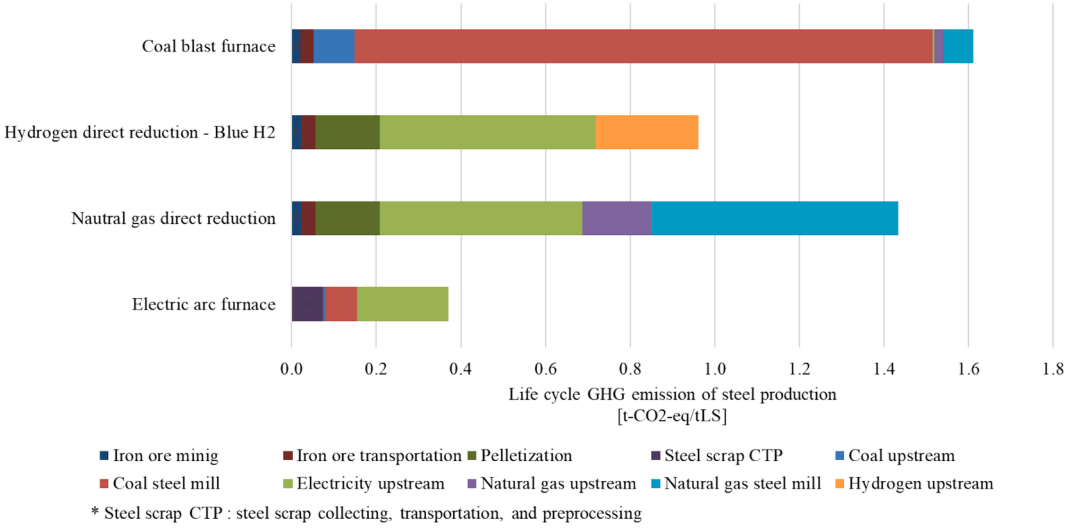


Fig.5. Life cycle of GHG emissions from steel production (Korean avg.).

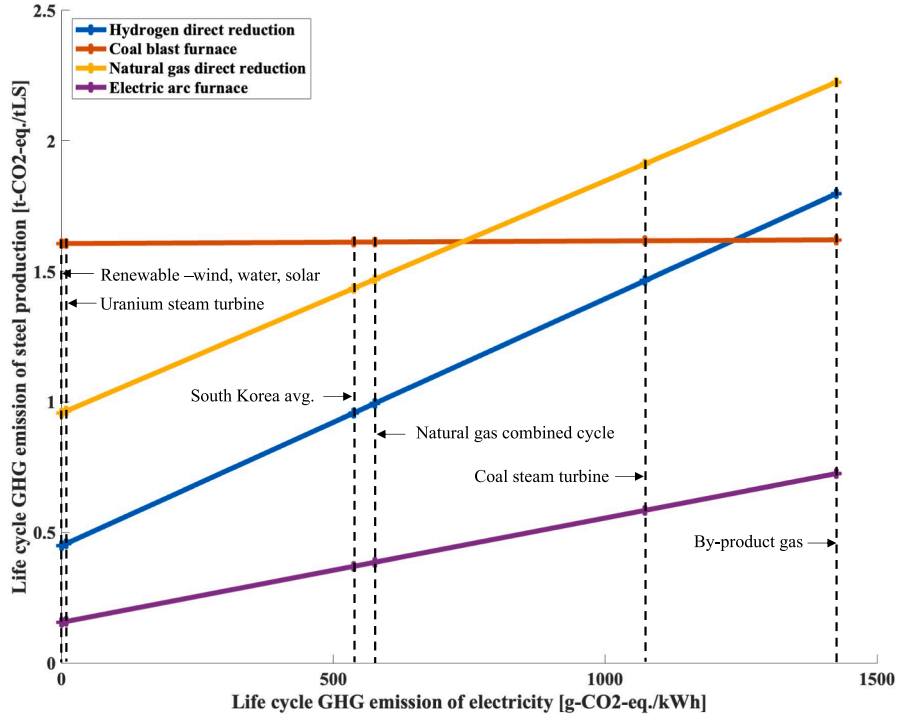


Fig.6. Life cycle of GHG emission for steel production by electricity generation methods.

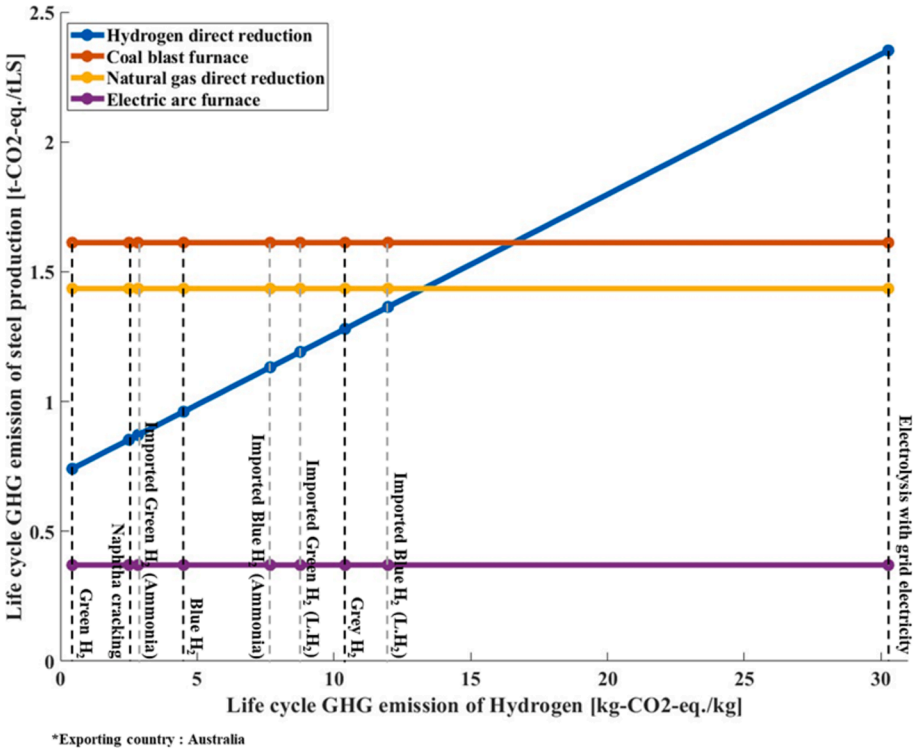


Fig.7. Life cycle of GHG emission for steel production by hydrogen generation methods.

with grid electricity hydrogen emits 1.5 times more greenhouse gases than conventional coal blast furnaces. Excluding hydrogen produced by electrolysis with grid electricity, the life cycle of greenhouse gas emissions from hydrogen direct reduction was lower than conventional coal blast furnaces or natural gas direct reduction. The life cycle of greenhouse gas emissions from hydrogen direct reduction using green hydrogen is approximately 54 % less than conventional coal blast furnaces. Using grey hydrogen for hydrogen direct reduction makes the process similar to natural gas direct reduction. However, it is noted that the life cycle of greenhouse gas emissions from hydrogen direct reduction using grey hydrogen is 155 kg-CO_2-eq./tLS less than from natural gas direct reduction. Comparing domestically produced blue hydrogen

with imported blue hydrogen, hydrogen direct reduction using domestically produced blue hydrogen shows the lowest emissions. In contrast, hydrogen direct reduction using liquefied blue hydrogen imported from Australia results in higher life cycle greenhouse gas emissions than using domestically produced grey hydrogen. Hydrogen direct reduction using green hydrogen imported in the form of ammonia from Australia emits 1.2 times more life cycle greenhouse gas emissions compared to using domestically produced green hydrogen. The method of import significantly affects greenhouse gas emissions. Importing hydrogen in the form of ammonia results in lower life cycle greenhouse gas emissions for hydrogen direct reduction compared to importing it as liquefied hydrogen. Therefore, for the countries like South Korea which must import hydrogen from overseas, hydrogen direct reduction will emit more GHG emissions than it will in countries that are able to import hydrogen via land transportation.

Fig. 8 shows the overall results considering both hydrogen and electricity production methods. The detailed values of Fig. 8 are provided in Supplementary Table S18. Electric arc furnaces are denoted as EAF, natural gas direct reduction as NGDR, and hydrogen direct reduction as H2DR. Hydrogen direct reduction is represented by considering both electricity and hydrogen production methods. Graphs with the same hydrogen usage are grouped together, and at the bottom of the graph, the electricity generation method used is indicated. Natural gas direct reduction and electric arc furnaces are presented considering only the power generation method.

In Fig. 8, it can be observed that there are no greenhouse gas emissions corresponding to the "fuel steel mill" for hydrogen direct reduction since there are no emissions within the steelmaking plant due to the use of electricity and hydrogen. For hydrogen direct reduction, when using both hydrogen produced by electrolysis with grid electricity and by-product gas power, the greenhouse gas emissions were very high at 3.2 t-CO2-eq./tLS. Similarly, when using hydrogen produced by electrolysis with grid electricity and coal steam turbine power, the emissions were calculated to be 2.9 t-CO2-eq./tLS, also indicating significant greenhouse gas emissions. Even when using renewable energy power for grid electrolysis hydrogen, the greenhouse gas emissions are not significantly reduced compared to conventional coal blast furnaces. Therefore, it can be inferred that using grid electrolysis hydrogen for hydrogen direct reduction is unsuitable.

Furthermore, it was confirmed that when grey hydrogen and by-product gas power are used for hydrogen direct reduction, greenhouse gas emissions reach 2.1 t-CO2-eq./tLS. When grey hydrogen and coal steam turbine power are utilized, emissions reach 1.8 t-CO2-eq./tLS. Both methods emit more greenhouse gases than conventional coal blast furnace steelmaking. Therefore, in the case of hydrogen direct reduction using grey hydrogen, employing electricity that is cleaner than or equal to the Korean average electricity could result in a more environmentally friendly steelmaking method than conventional coal blast furnaces.

Hydrogen direct reduction utilizing blue hydrogen emits lower greenhouse gas emissions across the entire process compared to coal blast furnaces, except in cases where by-product gas generation power is used. When blue hydrogen is paired with renewable energy generation, it emits a significantly reduced amount of greenhouse gases, approximately 28 % of the total emissions from coal blast furnaces.

Hydrogen direct reduction utilizing green hydrogen emits lower life cycle greenhouse gas emissions compared to coal blast furnaces, regardless of the type of power used. When renewable energy power and green hydrogen are combined, hydrogen direct reduction emits minimal greenhouse gases at 0.2 t-CO2-eq./tLS. This accounts for approximately 14 % of the total emissions from coal blast furnaces, positioning it as an exceptionally environmentally friendly steelmaking method, meaning that using renewable energy power for electric arc furnace steelmaking results in lower greenhouse gas emissions.

However, even when using renewable energy to eliminate greenhouse gas emissions from electricity usage and employing green hydrogen to mitigate emissions from hydrogen usage, the life cycle of greenhouse gas emissions from producing 1 ton of liquid steel through hydrogen direct reduction does not become zero. This is due to greenhouse gas emissions generated during the mining, transporting, and pelletizing iron ore. In particular, the greenhouse gas emissions from pelletizing iron ore are significant, highlighting the need for more environmentally friendly methods.

4.2. Sensitivity analysis

Sensitivity analysis was conducted on the input values used for the

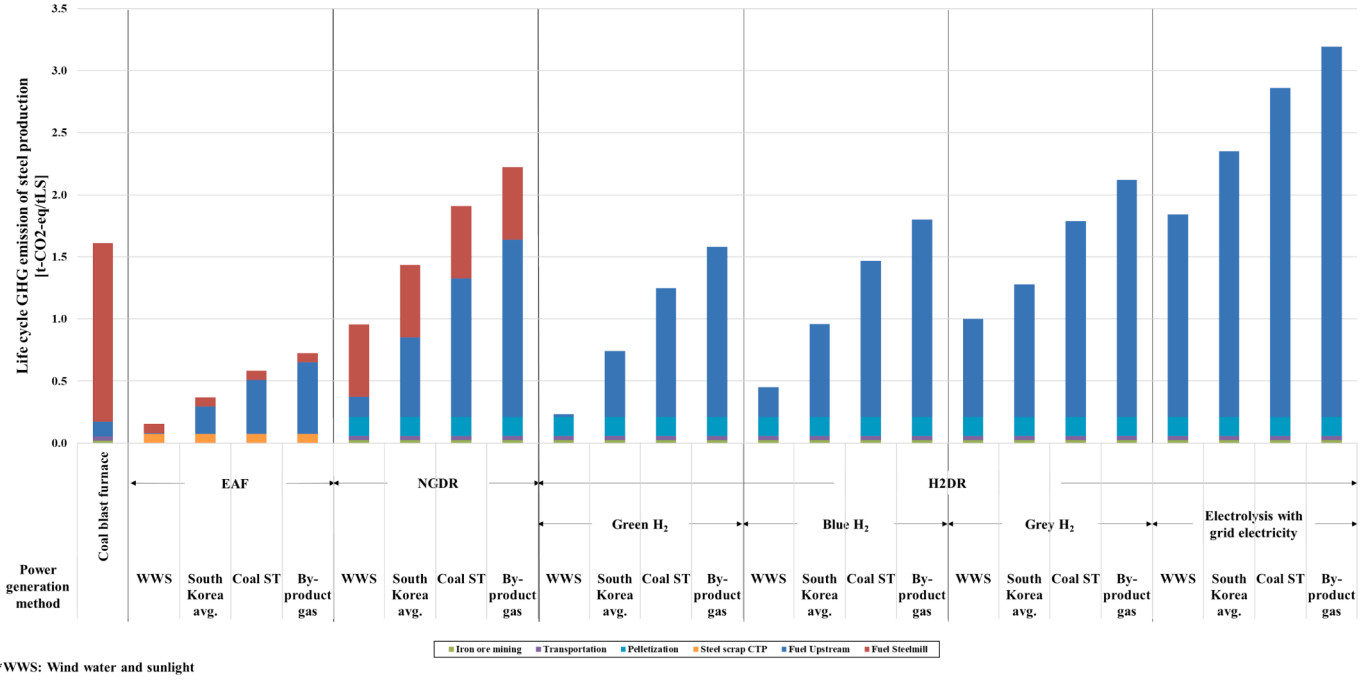


Fig.8. Life cycle of GHG emission for steel production.

life cycle assessment of steel production. The sensitivity analysis calculated the values as percentages when the input data used in the previous analysis increased or decreased by 5 %.

The sensitivity analysis of the coal blast furnace is shown in Fig. 9. The coal blast furnace was analyzed based on the iron ore consumption in the steel mill, coal consumption, electricity consumption, cargo payload when transporting iron ore, and distance. In the case of the coal blast furnace, it was found that the change in coal consumption had the most significant impact on the results of the life cycle analysis, with a variation of 4.53 %. Other factors besides coal consumption have a minimal impact of around 0.1 %. As a result, while other factors show little variation when input values change by 5 %, coal consumption exhibits significant differences. Therefore, it is crucial to use well validated value for this parameter. Notably, the coal values used in this study were validated to be appropriate for comparison with theoretical values.

The sensitivity analysis results of hydrogen direct reduction are presented in Fig. 10. Sensitivity analysis was conducted based on variations in the iron ore consumption, electricity consumption, hydrogen consumption, electricity, and coal consumption in the pelletization, cargo payload during iron ore transportation, and transportation distance, with blue hydrogen as the reference. In the case of hydrogen direct reduction, the variation in greenhouse gas emissions due to changes in electricity consumption was the most significant, as electricity consumption is substantial. The sensitivity to iron ore consumption was relatively high because changes in iron ore consumption also affect the amount of energy required for the pelletizing process. Since the pelletizing process uses coal and electricity, it was analyzed based on variations in energy usage. Similarly, it can be observed that variations in the transportation process do not have a significant impact on the life cycle analysis. The variations in the amounts of electricity and hydrogen used in hydrogen direct reduction significantly impact the resulting values. Notably, these were validated to be appropriate for comparison with theoretical values.

The sensitivity analysis results of natural gas direct reduction are depicted in Fig. 11. The sensitivity analysis for natural gas direct reduction was conducted similarly to hydrogen direct reduction. Natural gas direct reduction exhibited the greatest variability with changes in natural gas consumption, followed by electricity. Additionally, natural gas direct reduction showed a relatively large variation in energy usage for pelletizing as the amount of iron ore consumption increased. Similarly, factors such as transportation distance and cargo payload during iron ore transportation had minimal impact on natural gas direct reduction results, consistent with other steelmaking methods. The consumption of natural gas and electricity in natural gas direct reduction significantly influences the resulting values. Therefore, determining the usage of natural gas and electricity is crucial. Notably, in this study, the validity of natural gas usage was verified by comparing it with theoretical values.

The sensitivity analysis results of the electric arc furnace are shown in Fig. 12. The sensitivity analysis of the electric arc furnace encompassed various factors, including coal consumption, electricity consumption, steel scrap consumption, energy expended during steel scrap collection, transportation distances for prompt and obsolete scrap, diesel, and natural gas consumption for scrap preprocessing, as well as transportation distances and payloads associated with imported scrap. Sensitivity analysis of electric arc furnaces includes various factors due to the use of diverse types of steel scrap in steelmaking. Since electric power serves as the primary fuel in electric arc furnaces, variations in electricity consumption significantly impact result variations, albeit relatively minor, at around 3 %. Sensitivity analysis also revealed a high sensitivity to steel scrap consumption. In steel scrap preprocessing, which applies only to obsolete and imported scrap, the quantity of natural gas used has a greater impact than diesel usage. Therefore, in electric arc furnaces, the usage of electricity and coal is crucial in determining the resulting values. The electricity and coal data used were validated through comparison with other literature sources to ensure their validity.

5. Conclusions

This study calculated and compared the life cycle greenhouse gas emissions generated when producing 1 ton of liquid steel through coal blast furnaces, hydrogen direct reduction, natural gas direct reduction, and electric arc furnaces. In this study, the analysis was conducted based on South Korea, a representative country in steel production, heavily

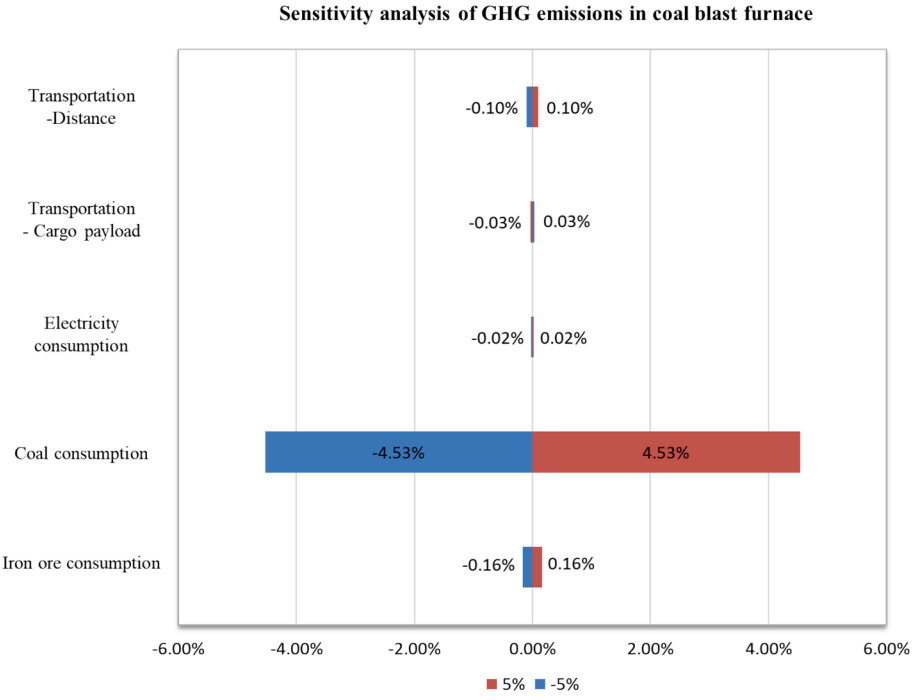


Fig.9. Sensitivity analysis: variation in the life cycle of GHG emissions for steel produced in a coal blast furnace.

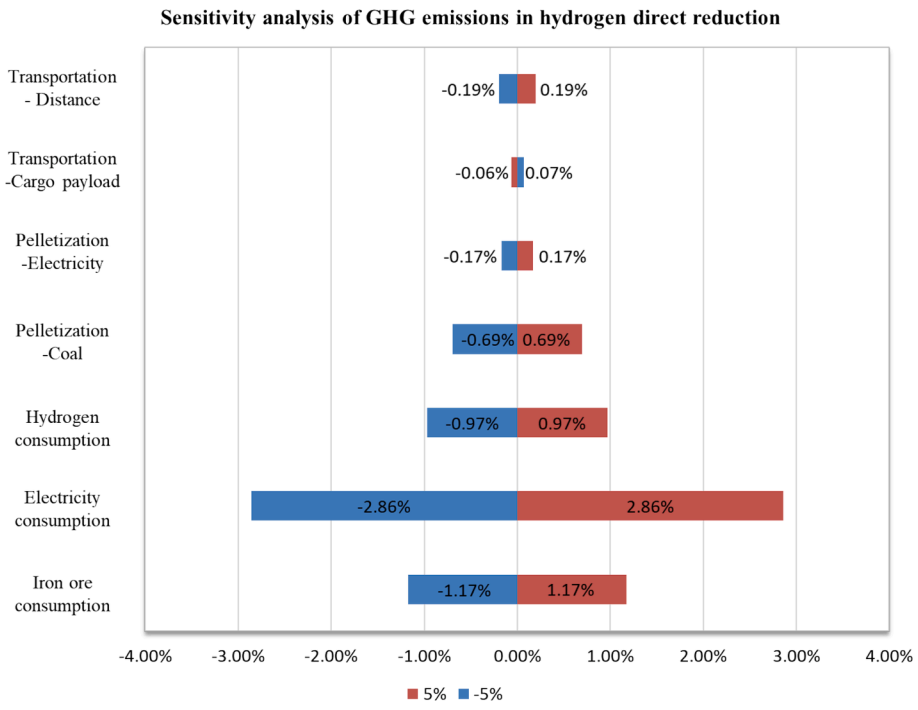


Fig.10. Sensitivity analysis of GHG emissions in hydrogen direct reduction.

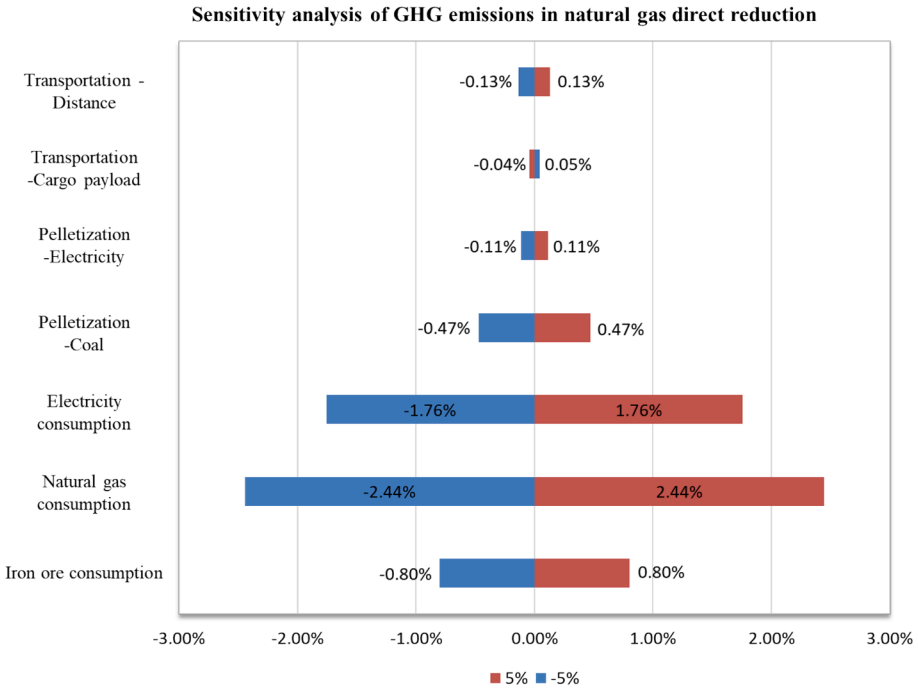


Fig.11. Sensitivity analysis of GHG emissions in natural gas direct reduction.

dependent on energy imports, and reliant solely on maritime transport for energy imports. It analyzed the life cycle of greenhouse gas emissions from steel production based on different electricity generation and hydrogen production methods. The findings from the study are as follows:

- The life cycle greenhouse gas emissions for coal blast furnace were calculated as 1612 kg-CO_2-eq./tLS, for natural gas direct reduction 1435 kg-CO_2-eq./tLS, for hydrogen direct reduction 961 kg-CO_2-eq./tLS, and for electric arc furnace 370 kg-CO_2-eq./tLS.
- Hydrogen direct reduction and natural gas direct reduction are more sensitive to changes in electricity usage due to higher electricity consumption compared to electric arc furnaces.
- Hydrogen direct reduction using renewable power emits 72 % less greenhouse gas emissions than conventional coal blast furnaces.
- When natural gas direct reduction utilizes coal steam turbine power or by-product gas steam turbine power, it is less environmentally friendly than conventional steelmaking methods. If renewable energy power is used in natural gas direct reduction, it emits 41 % less greenhouse gases than conventional coal blast furnaces.

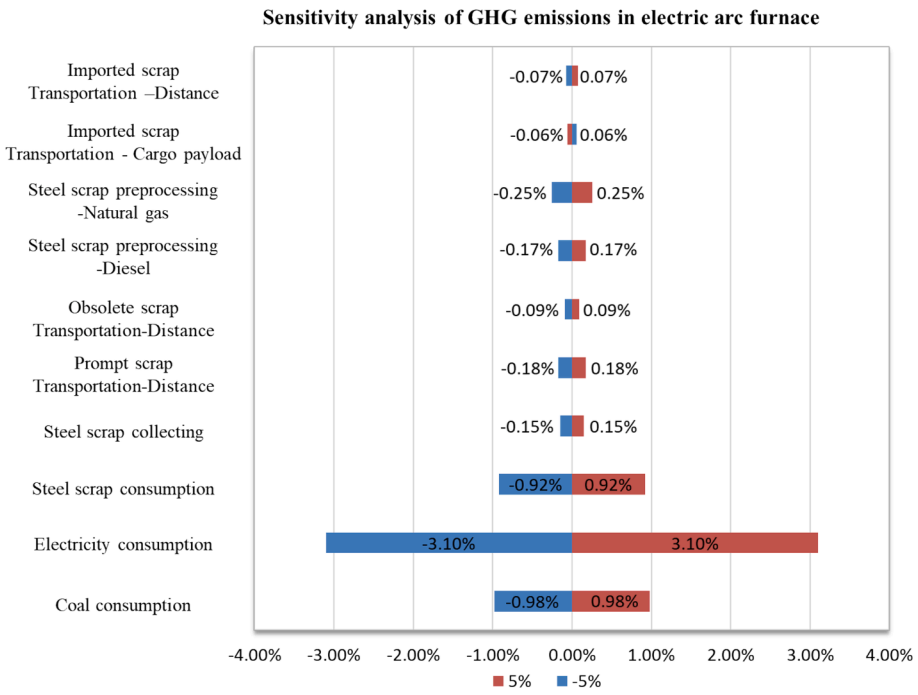


Fig.12. Sensitivity analysis of GHG emissions in an electric arc furnace.

- Hydrogen direct reduction using green hydrogen emits 54 % less greenhouse gases compared to conventional method. Hydrogen direct reduction using electrolysis with grid electricity for hydrogen production emits 1.5 times more greenhouse gases compared to conventional coal blast furnaces.
- Using green hydrogen and renewable electricity for hydrogen direct reduction results in 86 % less life cycle of greenhouse gas emissions compared to conventional coal blast furnaces.
- Comparing domestically produced blue hydrogen with imported blue hydrogen, hydrogen direct reduction using domestically produced blue hydrogen shows the lowest emissions.
- Hydrogen direct reduction using liquefied blue hydrogen imported from Australia results in higher life cycle greenhouse gas emissions than using domestically produced grey hydrogen.
- For countries such as South Korea, which rely on importing hydrogen from overseas, hydrogen direct reduction results in higher GHG emissions compared to countries capable of transporting hydrogen via land.
- Even when using green hydrogen and renewable electricity for hydrogen direct reduction, the life cycle of greenhouse gas emissions does not reach zero. This is due to the greenhouse gas emissions generated during the pelletization process, indicating the need for environmentally friendly pelletization methods.
- Hydrogen direct reduction using electrolysis with grid electricity for hydrogen production and by-product gas power emits 2 times more greenhouse gases compared to conventional coal blast furnaces.
- A sensitivity analysis was conducted on the input values used in the life cycle assessment. It was found that apart from energy consumption, the results were not sensitive to other factors. The validity of energy consumption was confirmed through comparison with various literature sources and theoretical calculations. Through this, the results obtained in this study are robust.

CRediT authorship contribution statement

Juha Lee: Writing – original draft, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gyuna Kwak:** Investigation, Data curation. **Yujin Jung:** Investigation, Data curation. **Wonjae Choi:** Writing – review & editing, Supervision, Project administration.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecmx.2024.100865.

Data availability

Data will be made available on request.

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