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# Theoretical Energy Consumption Analysis for Sustainable Practices in Iron and Steel Industry

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**Abstract:** Exploring theoretical energy consumption introduces a fresh perspective for energy-saving research within the iron and steel industry, with a primary focus on the energy expended during material transformation. Building upon the theory of theoretical energy consumption, this study meticulously investigates the theoretical energy consumption associated with each stage of the iron and steel making process, including coking, sintering, pelletizing, ironmaking, steelmaking, and hot rolling. The findings reveal that, under specific conditions, the theoretical energy consumption for each process is as follows: coking (2.59 GJ), sintering (1.36 GJ), pelletizing (1.02 GJ), ironmaking (8.81 GJ), steelmaking (−0.16 GJ), and hot rolling (0.76 GJ). Additionally, this study delves into the analysis of influencing factors on theoretical energy consumption. Using the coking process as an illustrative example, it is observed that the theoretical energy consumption in coking decreases with a reduction in both moisture and volatile content in coal. Under the specified conditions, the minimum theoretical energy consumption for each process is as follows: coking (2.51 GJ), sintering (0.98 GJ), pelletizing (0.67 GJ), ironmaking (8.38 GJ), steelmaking (−0.58 GJ), and hot rolling (0.07 GJ), respectively. This comprehensive analysis serves as a valuable resource for advancing sustainable practices in the iron and steel industry.

**Keywords:** theoretical energy consumption; iron and steel making process; thermodynamic analysis; influencing factor



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## 1. Introduction

The iron and steel industry (ISI), serving as a crucial cornerstone of the national economy, plays a substantial role in fostering economic and social development [1]. In recent decades, the global ISI has experienced rapid growth [2]. According to data from the World Steel Association, the worldwide crude steel output soared to $1.89 \times 10^9$ t in 2023 [3], with a significant portion, 53.97% ($1.02 \times 10^9$ t), originating from China. Recognized as a prototypical resource-and energy-intensive sector [4], the ISI typically consumes around 1370 kg of iron ore, 125 kg of scrap steel, 780 kg of coal, 270 kg of limestone, 450 kWh of electricity, and 3300 kg of freshwater to produce one tonne of crude steel [5].

As a prominent steel producer, China has undertaken significant initiatives to curtail energy consumption within the ISI. Over the past few decades, China's ISI has traversed distinct developmental phases: (i) the single equipment energy-saving phase, (ii) the system energy-saving stage, (iii) the energy flow and energy flow collaborative network stage, and (iv) the green and intelligent development stage [6]. Notably, the comprehensive energy consumption per tonne of crude steel has witnessed a remarkable reduction from 48.2 GJ in 1980 to 16.1 GJ in 2023 [7]. However, despite this progress, the total energy consumption of China's ISI has surged from $1.76 \times 10^9$ GJ in 1980 to $1.65 \times 10^{10}$ GJ in 2023, owing to the continuous escalation of crude steel output [8]. In the context of the escalating energy crisis and the push for the 'dual carbon' goal, the imperative of energy conservation and consumption reduction has gained heightened significance. This holds particularly true for the ISI, known for its intensive energy consumption [9].

The era of the single equipment energy-saving stage dates back to the 1980s. During that period, researchers concentrated their efforts on enhancing the thermal and exergy efficiency while minimizing energy losses in individual pieces of equipment, guided by the principles of the first and second laws of thermodynamics. It has been emphasized that effective measures to reduce energy loss and enhance efficiency involve adjustments to material structure, technological parameters, structural parameters, and so on [10–12]. For instance, Feng et al. [13] optimized the sintering cooling machine, aiming to maximize exergy output. Their work highlighted that optimizing the height of the sinter layer and adopting lower porosity, among other factors, can effectively improve the exergy output from waste heat recovery. Liu et al. [14] explored waste heat utilization in sintering beds, identifying that increasing the height of the sinter cooling bed and the moving speed of trolley can enhance both the quantity and quality of waste heat utilization. Liu et al. [15] performed the optimization of a coke oven with the goal of minimizing exergy loss and found that increasing the usage of gas coal can reduce the exergy loss during the coking process. Similarly, Liu et al. [16] performed the optimization of a blast furnace with the aim of minimizing exergy loss and found that the exergy loss of a blast furnace can be reduced by reducing the blast temperature and coal radio, and increasing the blast humidity, oxygen enrichment, top gas temperature, and slag basicity. Çamdali et al. [17] obtained optimal design parameters and operation conditions of an electric arc furnace (EAF) employing exergy analysis. Kaska et al. [18] improved the energy and exergy efficiencies of organic Rankine for power generation from waste heat recovery in ISI, and found that the evaporation pressure has a positive effect on energy efficiency and exergy efficiency.

Since the 1990s, the research on energy saving in ISI has shifted from the single equipment energy-saving phase to the system energy-saving phase [6]. It has greatly promoted the energy saving and consumption reduction in China's ISI. The theory of system energy conservation states that the objective of energy-saving in the ISI is (i) to reduce the consumption and energy carrying of the first type of energy carrier (such as iron ore, scrap, etc.), (ii) reduce the consumption and energy carrying of the second type of energy carrier (such as coke, coal, electricity, etc.), and (iii) recover the energy lost (such as sensible heat of iron and steel slag, sensible heat of flue gas, etc.). In accordance with this perception, a great many studies emerged one after another. For example, based on the proposed concept of the required energy, Na et al. [19] established an innovative energy efficiency evaluation method for the ISMP, and pointed out that recovering waste heat, adjusting the structure of products, and so on can improve energy efficiency of the ISMP. Wu et al. [20] analyzed the energy and exergy efficiency of the ISMP over a period of decades with the results showing that the exergy efficiency and energy efficiency of China's ISI has significantly improved. Zhang et al. [9] analyzed the utilization of waste heat in China's ISI and predicted the potential of energy conservation in the future. Fruehan et al. [21] and Martelaro [22] analyzed the theoretical minimum energy consumption of ISMP for selected condition. Based on a mixed-integer linear programming (MILP) model, Zhao et al. [23] optimized the utilization of by-product gas produced by the ISMP. Jiang et al. [24] built a thermodynamic model of the ISMP and optimized the energy utilization of the whole process. However, their studies were carried out from an almost ideal perspective, with a lack of analysis of the impact of actual materials on theoretical energy consumption, and without considering the limit of theoretical energy consumption.

In the energy and energy flow synergistic network stage, more studies focus on the coordinated relationship of material and energy to promote the efficient operation of the ISMP [25]. Considering material and energy flow, for example, Costa et al. [26] created an exergy-based life cycle inventory for a conventional integrated, semi-integrated, and new integrated ISMP. Sun et al. [27] pointed out that the current research on the coupling of material and energy flow is in its infancy and is facing challenges such as a lack of theoretical research, insufficient qualitative consideration of energy, and structural transformation. For the green and intelligent development stage, many studies have been carried out in order to promote the reduction in pollutant emissions in iron and steel enterprises and the intelligent control of the ISMP. For example, Sun et al. [28] established the material–energy–emission nexus of the typical steel enterprise and analyzed the key elements that affect these nexuses, including the purchased coke, exported cast iron, scrap steel ratio, and metallic yield. Zhang et al. [29] proposed an integrated material–energy–carbon hub and explored the links and influencing factors among material, energy, and carbon. Zhang et al. [30] performed the optimization of the carbon emissions and energy use of iron and steel enterprises and pointed out several key elements of $CO_2$ emission reduction and energy conservation, such as increasing the scrap ratio and pellet ratio. In addition, Tan et al. [31], Na et al. [32], and Wang et al. [33] explored the relationship between $CO_2$ emission reduction and energy consumption in the ISI.

To sum up, at present, the research on energy conservation and consumption reduction in the ISI focuses on the following aspects: (i) improving the energy efficiency (such as thermal efficiency and exergy efficiency) or reducing energy loss by analyzing and optimizing the energy utilization level of single equipment; (ii) saving energy and reducing its consumption in the ISMP by studying the matching relationship between upstream and downstream processes in the ISMP by taking the ISMP or a steel plant as a system; (iii) not only reducing energy consumption, but also reducing pollutant emissions (especially $CO_2$ emissions) by coupling energy and materials of the ISMP. The above research has led to great achievements in energy conservation and consumption reduction in the ISI in recent decades. However, these studies lack an in-depth exploration of the necessary energy consumption of the ISMP, embodying the following aspects: (i) there is not enough clarity about the level of theoretical energy consumption each process in the ISMP requires; (ii) it has not been discussed which factors affect the theoretical energy consumption of the ISMP in previous studies. The research on theoretical energy consumption is of great significance to energy saving and consumption reduction in the ISI, which determines the limit value of energy consumption in the ISI and provides new thinking for energy saving of the ISI. In this study, the theoretical energy consumption of the typical ISMP is hereby gradually derived by considering the actual production situation. Then, the influencing factors of theoretical energy consumption are discussed.

## 2. Theoretical Methods

### *2.1. Scope of Study: A BF-BOF Process*

The research focus of this study, as illustrated in Figure 1, centers around a BF-BOF process. This comprehensive process encompasses the raw material preparation process, ironmaking process, steelmaking process, and rolling process.

**Raw Material Preparation Process:** This process generally includes coking, sintering, and pelletizing processes. Coking is a process that involves the metamorphosis of coal into coke through rigorous high-temperature heating in a meticulously controlled, air-isolated environment. This intricate transformation ensures that the coal attains the desired properties, crucial for its utilization in various industrial applications. In the pelletizing and sintering stage, iron ore is meticulously combined with flux and fuel, undergoing a meticulous sequence of roasting and cooling procedures. These procedures are carefully orchestrated to ensure the optimal physical and chemical transformation of the ore. Ultimately, this intricate process leads to the formation of sinter or pellets, which are crucial raw materials for the blast furnace iron-making processes.

**Blast Furnace Ironmaking Process:** The aim here is to reduce iron oxide to molten iron under high-temperature conditions. Iron ore serves as the primary raw material, with coke playing a dual role as both a fuel and a reducing agent.

**Steelmaking Process:** In the steelmaking process, molten iron and scrap steel undergo heating or melting, followed by the removal of unwanted elements such as carbon, silicon, manganese, sulfur, phosphorus, and others, to produce semi-finished products. This process typically comprises basic oxygen furnace (BOF) steelmaking, refining, and continuous casting stages.

**Rolling Process:** The rolling process shapes steel products with specific metal properties under controlled temperature and pressure. This step encompasses both hot rolling and cold rolling.

This study aims to provide a comprehensive analysis of the entire BF-BOF process, examining each phase's theoretical energy consumption and exploring avenues for enhancing energy efficiency in this critical industrial context.

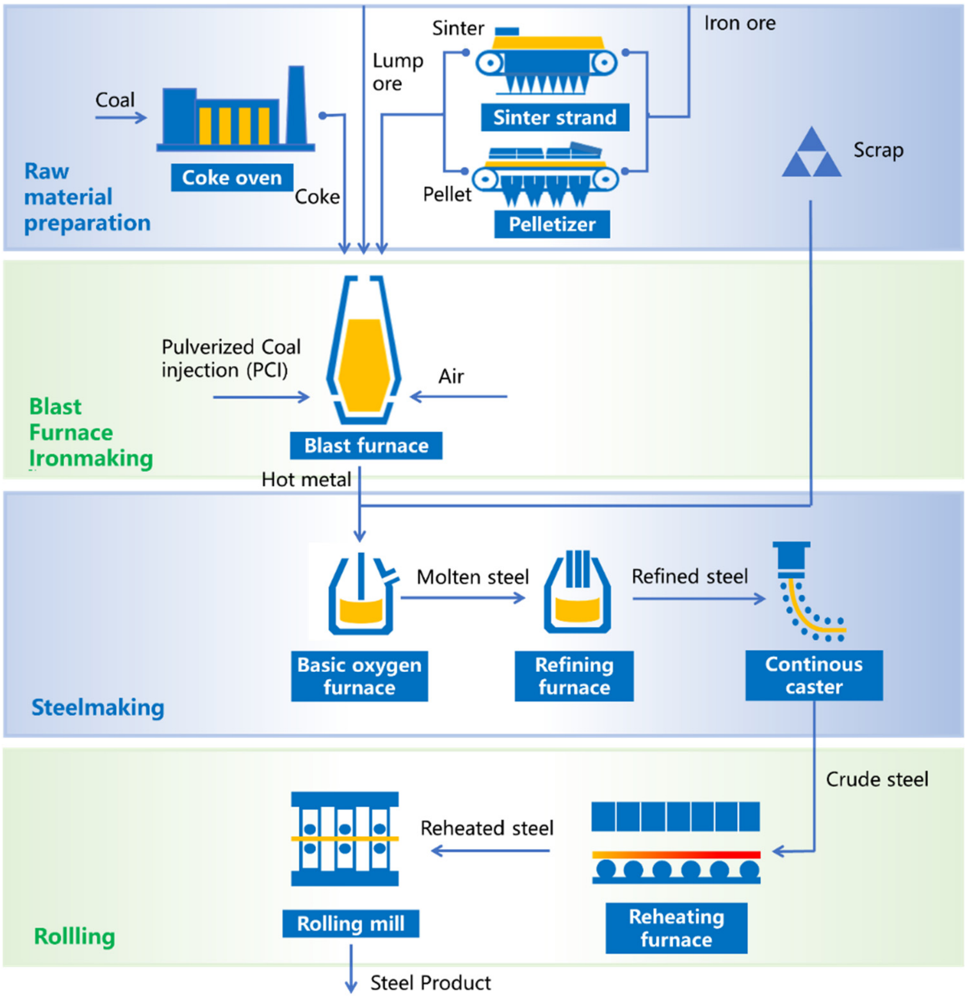



**Figure 1.** Scope of this study: a BF-BOF process.

## 2.2. Theoretical Energy Consumption

Importantly, when a special substance is changed from one state to another, or is transformed into another substance, it needs to overcome a certain resistance. When the energy provided is just such that the substance overcomes this resistance, this energy provided is called the theoretical energy consumption. The production of steel products can be regarded as the process that iron is driven by carbon to complete the production of products according to certain procedures. This driving force is the theoretical energy consumption to produce products. To sum up, it is determined that the theoretical energy consumption is the energy that must be consumed to produce a specific product under a given raw material condition. According to the above concept, there is, undoubtedly, also theoretical energy consumption in ISMP. Therefore, it relates to a series of physical and chemical reactions from raw materials to products, such as sensible heat, phase change heat, reaction heat, and so on.

As mentioned earlier, a series of physical and chemical reactions take place in the ISMP. Taking blast furnace ironmaking as an example, it includes evaporation and decomposition of water, direct reduction of iron ore, indirect reduction of iron ore, slag formation and limestone decomposition, as shown in Figure 2. The energy consumed in these procedures can be divided into sensible heat, phase change heat, reaction heat, and dissolution heat. Therefore, the theoretical energy consumption can be calculated by

$$TEC = \Delta H_s + \Delta H_p + \Delta H_r + \Delta H_s + \cdots \tag{1}$$

where *TEC* is the theoretical energy consumption, kJ; $\Delta H_S$ is the sensible heat of the material, kJ; $\Delta H_p$ is the phase change heat, kJ; $\Delta H_r$ is the reaction heat, kJ; and $\Delta H_s$ is the dissolution heat, kJ.

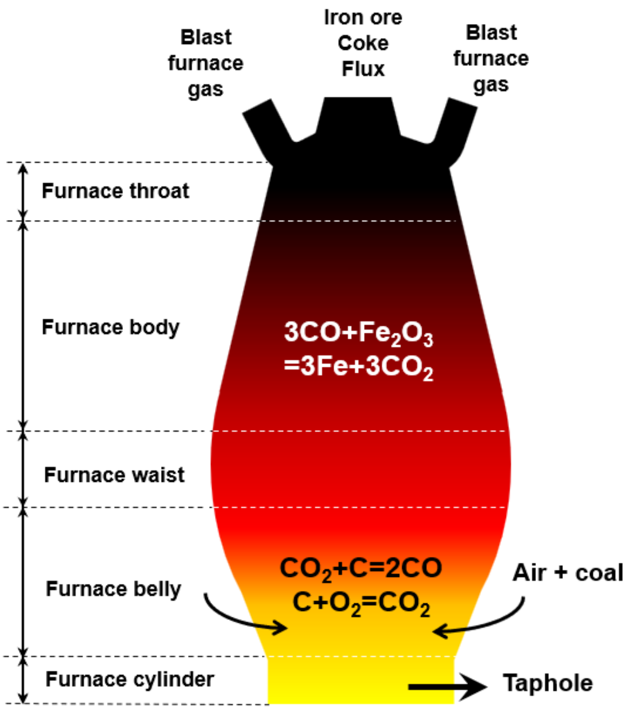



**Figure 2.** Structure and reaction mechanism of blast furnace ironmaking.

(1) **Sensible heat**

The change in temperature leads to the change in carrying energy of materials. In the process of iron and steel production, the sensible heat is involved in many aspects, such as heating billet and molten iron. In this study, the change in sensible heat caused by temperature is calculated by

$$\Delta H_s = \int_{T_1}^{T_2} mC_p dT \tag{2}$$

where $T_1$ and $T_2$ represent the initial and terminal temperatures of material, K; $m$ represents the mass of material, kg; $C_p$ represents the specific heat capacity of material at constant pressure, kJ/(kg·K); and $t$ represents the temperature of material, K.

(2) **Phase change heat**

The heat of phase change is the heat absorbed or released by a substance from one state (or phase) to another at a same temperature. Generally, the heat of phase change includes the melting heat from solid phase to liquid phase, the evaporation heat from the liquid phase to gas phase and the sublimation heat from solid phase to gas phase. Among them, the calculation method of melting heat is as follows:

$$\Delta H_m = mRT_m \tag{3}$$

where $R$ represents the molar gas constant; and $T_m$ represents the melting point temperature of material, K.

The evaporation heat is calculated by

$$\Delta H_e = 1.963mRT\frac{lnP_C - 1}{0.93 - \frac{T_b}{T_c}} \tag{4}$$

where $P_C$ is the critical pressure, Pa; $T_b$ is the normal boiling point temperature of material, K; and $T_C$ is the critical temperature of material, K.

The sublimation heat is the sum of melting heat and evaporation heat, which is calculated by

$$\Delta H_b = \Delta H_m + \Delta H_e \tag{5}$$

(3) **Reaction heat**

The energy is absorbed or released by a chemical reaction of a substance when it returns to its initial temperature. The iron and steel production process involve a lot of chemical reactions, such as reduction reaction of iron oxide, carbon oxidation reaction, carbonate decomposition reaction, etc. For example, the reaction heats of the two main chemical reactions occurring in the high- and low-temperature zones of blast furnace are given below.

$$\mathrm{Fe_2O_3 + 3CO = 2Fe + 3CO_2} \;\; \Delta H_{298\ K} = -28.5\ \mathrm{kJ/mol} \tag{6}$$

$$\mathrm{FeO + C(coke) = Fe + CO} \;\; \Delta H_{298\ K} = 154\ \mathrm{kJ/mol} \tag{7}$$

(4) **Dissolution heat**

The solution heat is the heat released or absorbed in the process of substance dissolution. The heat of dissolution is not discussed in this study.

In addition, the following assumptions are made in exploring the theoretical energy consumption of the ISMP:

- The burning loss of material not considered;
- The heat loss of furnace body is not considered;
- Energy consumption and material loss caused by transportation are not considered, because these can be avoided as much as possible in actual production;
- The casting is only physical cooling, so the theoretical energy consumption is 0 kJ;
- The refining is closely related to user needs, which will not be discussed in this paper;
- The energy consuming working medium (such as electricity, nitrogen, etc.) Consumed in the production process is not studied in this paper.
- The error in this study was limited to within 5%, in order to ensure the accuracy of the data.

## 3. Data Sources

The parameters involved generally include three categories: (1) quality and composition parameters of material, such as iron content in iron ore, iron content in molten iron, etc.; (2) process parameters, such as tapping temperature, sintering temperature, coking temperature, etc.; (3) thermodynamic parameters of materials, such as specific heat capacity and reaction enthalpy. The main data sources are as follows:

**Quality and composition parameters of material and product:** The material composition dataset is predominantly derived from actual production experience, while the production volume of the products is determined through the application of the principles of the law of conservation of mass along with empirical formulas. By aligning with actual operational parameters, they offer a comprehensive depiction of practical scenarios and facilitate nuanced analyses.

**Process Parameters:** The determination of process parameters is derived from both actual enterprise experience and relevant literature research, thereby enhancing the applicability and relevance of the research.

**Specific Heat Capacity and Enthalpy Values:** These fundamental metrics are diligently sourced from pertinent data tables through meticulous scrutiny. By conducting thorough searches, the study ensures accuracy and reliability in capturing essential properties crucial for analysis. Similarly, the investigation maintains a stringent approach in sourcing reaction enthalpy values, upholding standards of precision and integrity throughout the research endeavor.

## 4. Results and Discussion

The theoretical energy consumption of the iron and steel making process investigated in this study is centered around the production of one tonne of products. The theoretical energy consumption for each individual process is detailed as follows.

### *4.1. Investigating Theoretical Energy Consumption in Coking Process*

The coke formed by coal coking serves as high-quality fuel, reducing agent, and supporting framework for blast furnace. The coking process of coal can be divided into the following: (1) drying and preheating stage (approximately below 350 °C), where water and adsorbed gasses in the coal are released; (2) stages of coal plastic mass formation (approximately 350~480 °C), where a viscous gas–liquid–solid mixture (coal plastic mass) is formed; (3) stages of semi-coke formation (approximately 480~650 °C), where the coal plastic mass forms a semi-coke; (4) stages of coke formation (approximately 650~1000 °C), where a large amount of gas (containing $H_2$, $CH_4$, CO, $H_2S$, alkanes, olefins, aromatics, etc.) is generated as semi-coke forms coke [34]. It is worth noting that coal pretreatment and dry quenching are not within the scope of this study. The theoretical energy consumption of the coking process is discussed by the following several steps, as shown in Table 1. In the initial step (Step I), the focus is on volatiles and ash. The assumption is made that the composition of coal is fixed carbon, volatiles, and ash. Upon heating with isolated air, the first half of coking produces tar, crude benzene, COG, and ammonia, while the remaining COG and ammonia are generated in the second half. Coke formation occurs at a temperature of 1273 K, with the overall process resulting in a consumption of 2.01 GJ. In Step II, moisture becomes a factor. In addition to fixed carbon, volatile, and ash, a certain quantity of water is present in the coal. Here, it is assumed that the moisture content is 8%. Consequently, the overall theoretical energy consumption for the entire coking process is determined to be 2.59 GJ.

**Table 1.** Theoretical energy consumption of coking process.

| Items | | Product (Coke) Components | | TEC/(GJ/t-Coke) |
|---|---|---|---|---|
| **Steps** | **Hypothesis** | **C/%** | **Ash/%** | |
| I | Ash is considered. | 90 | 12% | 2.01 |
| II | Moisture is considered. | 90 | 12% | 2.59 |

Furthermore, the influencing factors of theoretical energy consumption in the coking process are analyzed in this study. It is found that the ash content in coal has little effect on the theoretical energy consumption because the ash content in coal is just heated and then goes directly into the coke. However, the more ash content in coal, the more ash in the coke, which greatly reduces the quality of the coke. Therefore, in order to improve the quality of the coke, it is necessary to reduce the ash content in coal. The analysis also found that the moisture and volatile matter in coal have a great influence on the theoretical energy consumption of the coking process. Referring to the current status of coal used in the coking process (i.e., a coal moisture content of 7~11%, and a coal volatile content of 25~35%), this study obtains the theoretical energy consumption of the coal with a different moisture and volatile content, as shown in Figure 3. It can be seen that the theoretical energy consumption of the coking process decreases with the decrease in the moisture and volatile content in coal. When the moisture content is 7% and the volatile content is 20% in coal, it is the lowest theoretical energy consumption in all cases studied, which is 2.49 GJ. To sum up, the moisture, volatile and ash content in coal is all unfavorable to the theoretical energy consumption of coking, so it is necessary to reduce these as much as possible in the coking process.

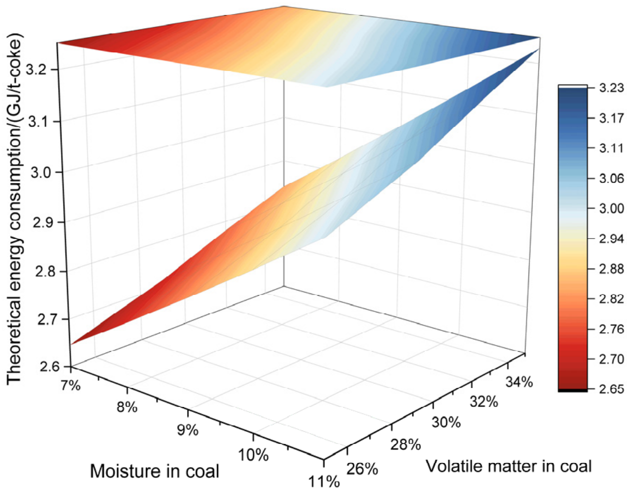



**Figure 3.** Influencing factors of theoretical energy consumption in coking process.

### *4.2. Investigating Theoretical Energy Consumption in Sintering Process*

The sintering process is that iron ore mixed with flux is roasted at a high temperature and then cooled to produce sinters used as the raw material in the blast furnace with a certain basicity and performance. It includes the evaporation and condensation of water, decomposition of carbonate and iron oxide, consolidation of sinter, and removal of other impurities. The theoretical energy consumption of the sintering process is systematically discussed through five distinct steps, outlined in Table 2. In Step I, the consideration centers on pure $Fe_2O_3$, CaO, and $SiO_2$. It is assumed that the sinter with an alkalinity of 1.8 and 56% of iron content is produced by roasting at 1573 K by taking pure $Fe_2O_3$, CaO, and $SiO_2$ as the raw material. The energy consumption of such a process is 1.21 GJ. Proceeding to Step II, gangue becomes a focal point. In addition to $SiO_2$ and CaO, the raw materials also encompass MgO and $Al_2O_3$. Assuming the produced sinters contain 3% MgO and 2% $Al_2O_3$, heated to 1573 K, resulting in sinters with TFe = 56.0%, $\omega_{CaO}$ = 9.6%, $\omega_{SiO2}$ = 5.4%, $\omega_{MgO}$ = 2.0%, and $\omega_{Al2O3}$ = 3.0%, the energy consumption for this process is calculated as 1.22 GJ. Moving to Step III, the consideration shifts to FeO. In the process of high-temperature roasting, part of the iron oxide will be reduced to ferrous oxide. It is assumed that the sinters produced contain 8% ferrous oxide. The energy consumption of such a process is 1.39 GJ. In Step IV, sulfur and carbonate are accounted for. Sulfur in minerals exists as FeS2, oxidized to FeS and $SO_2$ during high-temperature roasting, entering sinters and dust, respectively. Limestone, comprising calcium carbonate, is used instead of lime for smelting, incurring energy consumption for decomposition. Assuming 50% of sulfur in iron ore enters the sinter as FeS, and all solvents are limestone, the energy consumption for the entire process is 1.65 GJ. Moving to Step V, moisture is introduced. Building on Step IV, the mixture contains an additional 8% moisture, resulting in an energy consumption of 1.86 GJ. The sintering temperature is considered to be 873 K in step VI. In practice, the sintering can be completed when the temperature of the ground material layer reaches 873 K, because the bottom ventilation is adopted. At this juncture, the theoretical energy consumption of the sintering process is determined to be 1.36 GJ.

**Table 2.** Theoretical energy consumption of sintering process.

| Items | | Product (Sinter) Components | | | | | | TEC/(GJ/t-Sinter) |
|---|---|---|---|---|---|---|---|---|
| **Steps** | **Hypothesis** | **Tfe/%** | **R** | **MgO/%** | **$Al_2O_3$/%** | **FeO/%** | **S/%** | |
| I | $Fe_2O_3$, CaO, and $SiO_2$ are considered. | 56 | 1.8 | - | - | - | - | 1.21 |
| II | Gangue is considered. | 56 | 1.8 | 3 | 2 | - | - | 1.22 |
| III | FeO is considered. | 56 | 1.8 | 3 | 2 | 8 | - | 1.39 |
| IV | Sulfur and carbonate are considered. | 56 | 1.8 | 3 | 2 | 8 | 0.1 | 1.65 |
| V | Moisture is considered. | 56 | 1.8 | 3 | 2 | 8 | 0.1 | 1.86 |
| VI | The sintering temperature is 873 K. | 56 | 1.8 | 3 | 2 | 8 | 0.1 | 1.36 |

Notes: Tfe represents the content of Fe; *R* represents alkalinity and is calculated by $CaO/SiO_2$.

Furthermore, some factors affecting the theoretical energy consumption of the sintering process are discussed. Through an analysis, it is found that the FeO content in sinter, the content of moisture and iron in raw sinter ore, and the flux composition have a great influence on the theoretical energy consumption of the sintering process. A certain amount of water must be maintained in the sintering raw materials, about 7~8%. It can be seen that reducing the quantity of water has limitations on reducing the energy consumption. $Fe_2O_3$ in the raw material often reacts with carbon monoxide, a reducing gas, produced by carbon oxidation to form FeO. Generally, the amount of FeO contained in sinter is less than 10%. The iron content of raw materials is also an important factor affecting the energy consumption of sintering process. When the iron content in raw materials is high, the input of flux must be reduced, resulting in reduced energy consumption. Figure 4 plots the theoretical energy consumption for different iron ratios and ferrous oxide contents FeO contained in sinters. When the iron content of the raw material is 60% and the FeO content of sinter is 0%, it is the lowest theoretical energy consumption in all cases studied, which is 0.98 GJ. It can be seen that increasing the carbonate and iron content of the raw material and reducing the FeO content of sinter are of positive significance for reducing the theoretical energy consumption of the sintering process.

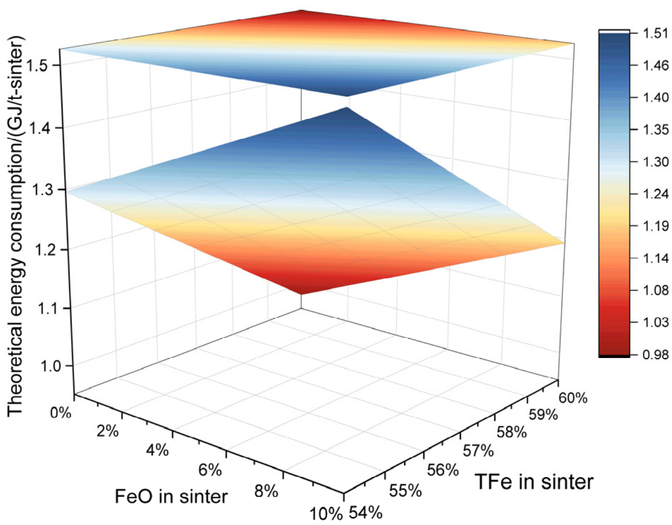



**Figure 4.** Influencing factors of theoretical energy consumption in sintering process.

### 4.3. Investigating Theoretical Energy Consumption in Pelletizing Process

The thermal reaction in the pelletizing process is very similar to that in the sintering process except for the difference in raw material. The firing of pellets is divided into drying, preheating, roasting, soaking, and cooling stages. The examination of the theoretical energy consumption of the pelletizing process unfolds across various steps, elucidated as follows. In Step I, the raw material comprising CaO, $SiO_2$, and $Fe_2O_3$ is subjected to heating at 1573 K to yield pellets. Step II incorporates the consideration of MgO and $Al_2O_3$. Step III introduces a composition where the raw material includes not only iron oxide but also 20% ferrous oxide. Sulfur and carbonate are taken into account in Step VI, while Step V involves the inclusion of an extra 8% moisture in the raw material. The detailed breakdown of the theoretical energy consumption for the pelletizing process is presented in Table 3.

**Table 3.** Theoretical energy consumption of pelletizing process.

| Items | | Product (Pellet) Components | | | | | TEC/(GJ/t-Pellet) |
|---|---|---|---|---|---|---|---|
| **Steps** | **Hypothesis** | **TFe/%** | **R** | **MgO/%** | **$Al_2O_3$/%** | **S/%** | |
| I | $Fe_2O_3$, CaO, and $SiO_2$ are considered. | 63 | 0.25 | - | - | - | 1.19 |
| II | Gangue is considered. | 63 | 0.25 | 2.5 | 1.5 | - | 1.20 |
| III | FeO is considered. | 63 | 0.25 | 2.5 | 1.5 | - | 0.78 |
| IV | Sulfur and carbonate are considered. | 63 | 0.25 | 2.5 | 1.5 | 0.1 | 0.82 |
| V | Moisture is considered. | 63 | 0.25 | 2.5 | 1.5 | 0.1 | 1.02 |

Similarly, the factors affecting the theoretical energy consumption of the pelletizing process are analyzed. It is found that FeO content in the raw material has a great influence on the theoretical energy consumption of the pelletizing process. Therefore, this study investigated the theoretical energy consumption of different FeO contents in the raw materials, as shown in Figure 5. With the increase in FeO contents in the raw material, the theoretical energy consumption shows a decreasing trend. When the FeO content in the raw material is 30%, the theoretical energy consumption is the lowest in all cases studied, which is 0.67 GJ.

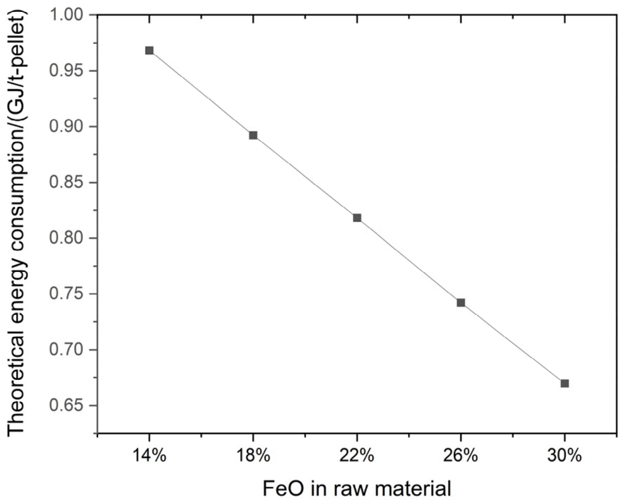



**Figure 5.** Influencing factors of theoretical energy consumption in pelletizing process.

### 4.4. Investigating Theoretical Energy Consumption in Ironmaking Process

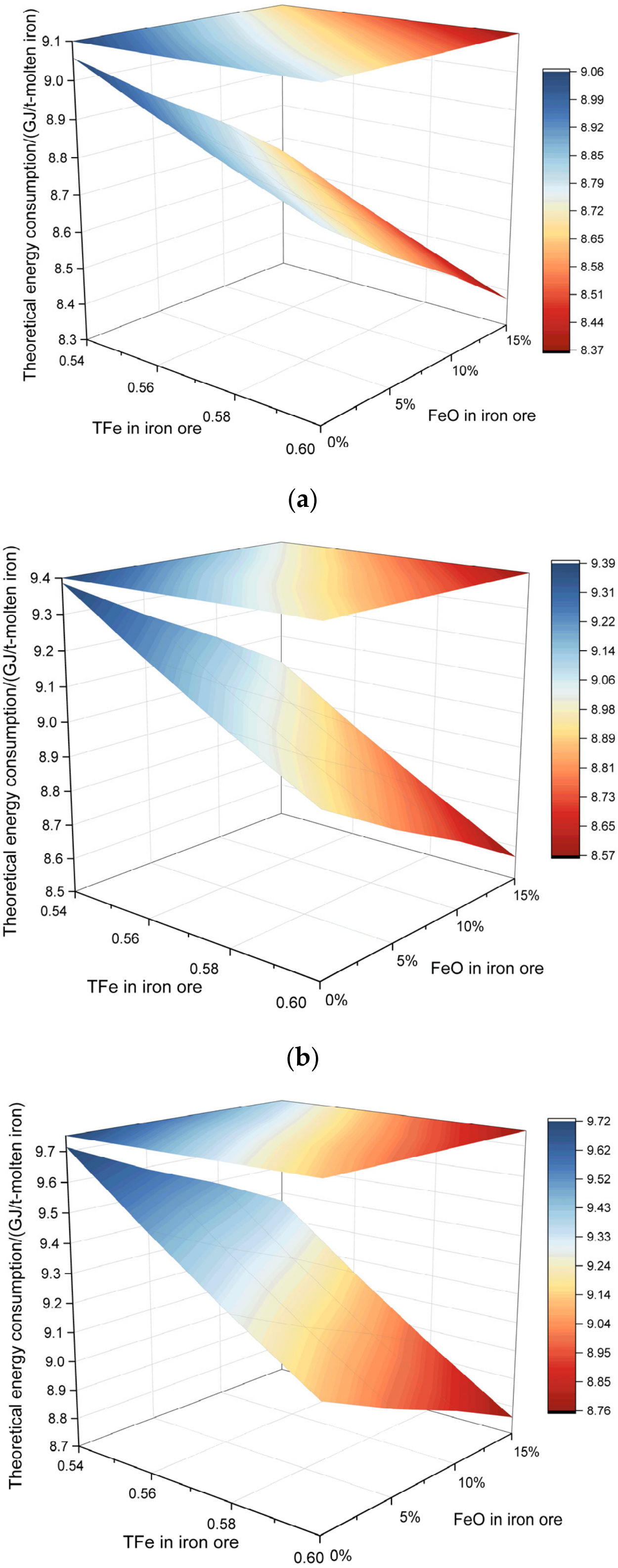
The theoretical energy consumption of the ironmaking process is discussed by the following several steps, as shown in Table 4. In Step I, pure $Fe_2O_3$ and C are considered. It is assumed that pure iron oxide (298 K) and carbon (298 K) are used as raw materials, which are decomposed and heated to form molten iron with the temperature of 1723 K and the carbon content of 4.3%. In such a process, the total energy consumption is 8.06 GJ.

In Step II, gangue is considered. There is a certain amount of gangue in iron ore, which is composed of alumina, manganese oxide, and silicon oxide. It requires calcium oxide (typically lime, limestone, etc.) to transform them to slag. In this step, it is assumed that the slag amount is 350 kg and its alkalinity is 1.08. In such a reaction, part of manganese oxide and silicon oxide is reduced into molten iron, which is assumed to contain 4.3% carbon, 0.5% silicon, and 0.5% manganese. The energy consumption of the whole process is 8.94 GJ. In Step III, FeO is considered. Except for $Fe_2O_3$, iron ore used in the ironmaking process also contains a certain amount of FeO. It is assumed that there is 10% ferrous oxide in the raw material, and 20% of this FeO is in the form of $Fe_3O_4$. The energy consumption of such a process is 8.64 GJ. P and S are considered in Step IV. There is some sulfur and phosphorus in the actual raw material. Phosphorus enters molten iron after it is decomposed. Then, 95% of the sulfur is oxidized to $SO_2$, which enters the flue gas, and 5% of the sulfur enters the molten iron. It is assumed that the molten iron produced contains 4.3% carbon, 0.03% sulfur, 0.5% silicon, 0.03% phosphorus, and 0.5% manganese. The energy consumption of such a process is 8.68 GJ. In step V, carbonate decomposition is considered. In order to save cost, limestone is used instead of lime in the ironmaking process. It is assumed that all fluxes are limestone. Therefore, the energy consumption of the whole process is 8.81 GJ.

**Table 4.** Theoretical energy consumption of ironmaking process.

| **Items** | | **Product (Molten Iron) Components** | | | | | | ***TEC*/(GJ/t-Molten Iron)** |
|---|---|---|---|---|---|---|---|---|
| **Steps** | **Hypothesis** | **Fe/%** | **C/%** | **Mn/%** | **Si/%** | **P/%** | **S/%** | |
| I | Pure $Fe_2O_3$ and C are considered. | 95.70 | 4.30 | - | - | - | - | 8.06 |
| II | Gangue is considered. | 95.70 | 4.30 | 0.50 | 0.50 | - | - | 8.94 |
| III | FeO is considered. | 95.70 | 4.30 | 0.50 | 0.50 | - | - | 8.64 |
| IV | P and S are considered. | 94.64 | 4.30 | 0.50 | 0.50 | 0.03 | 0.03 | 8.68 |
| V | Carbonate decomposition is considered. | 94.64 | 4.30 | 0.50 | 0.50 | 0.03 | 0.03 | 8.81 |

Through an analysis, it is found that the content of Fe, FeO, and carbonate-containing flux in the iron ore has a great impact on the theoretical energy consumption in the ironmaking process. As shown in Figure 6, the theoretical energy consumption in the ironmaking process decreases with the increase in the content of Fe and FeO in the iron ore and the content of carbonate-containing flux. When the content of Fe in the iron ore increases, the consumption of iron ore produced by a tonne of molten iron and the amount of iron slag decreases, resulting in a decrease in theoretical energy consumption in the ironmaking process. When the content of ferrous oxide in the iron ore increases, the energy consumption per mole of molten iron produced is reduced compared to that of iron oxide. When the carbonate-containing flux is increased, a large amount of heat is required to decompose these calcium carbonate and magnesium carbonate, resulting in an increase in energy consumption. When the content of Fe in the iron ore is 60%, the ferrous oxide content in the iron ore is 15%, and the carbonate-containing flux is 0, the theoretical energy consumption of the ironmaking process is the lowest among all the cases studied, which is 8.38 GJ/t. It can be seen that reducing the input of carbonate-containing flux and increasing the grade and ferrous oxide content of iron ore are effective measures to reduce the energy consumption of the ironmaking process.




(**a**)



(**b**)



(**c**)

**Figure 6.** Influencing factors of theoretical energy consumption in ironmaking process. (**a**) n($CaCO_3$)/n(CaO) = 0. (**b**) n($CaCO_3$)/n(CaO) = 1/4. (**c**) n($CaCO_3$)/n(CaO) = 1/2.

*4.5. Investigating Theoretical Energy Consumption in Basic Oxygen Furnace Steelmaking Process*

The basic oxygen furnace steelmaking process is to obtain the best performance of molten steel by controlling beneficial elements such as C, Si, Mn, Ni, and Cr and eliminating unneeded elements such as P, S, O, and N. The theoretical energy consumption of the steelmaking process is discussed via the following three steps, and is shown in Table 5. Liquid iron (1723 K) and carbon are considered Step I. In this step, it is assumed that molten iron with the temperature of 1723 K and the carbon content of 4.3% is smelted to form molten steel with the temperature of 1923 K and the carbon content of 0.1%. In addition, it is also assumed that 90% of the carbon is oxidized to CO, and the rest is oxidized to $CO_2$. The energy consumption of this process is −0.31 GJ. In Step II, Si, Mn, P, and S contained in molten iron are considered. In this step, molten iron contains not only 4.3% carbon, but also 0.5% manganese, 0.5% silicon, 0.03% phosphorus, and 0.03% sulfur. Silicon is oxidized to form silicon oxide into slag. Part of manganese and phosphorus are oxidized to form manganese oxide and phosphorus pentoxide into slag. The rest goes into the molten iron. Part of sulfur is oxidized to form $SO_2$ and enters flue gas, and the rest enters the slag. At this time, the molten steel contains 0.1% carbon, 0.15% manganese, 0.02% phosphorus, and 0.02% sulfur. The steel slag mass and alkalinity are 120 kg and 3.5, respectively. The energy consumption of this process is −0.53 GJ. Scrap (298 K) is considered in Step III. In the process of modern steelmaking, a certain amount of scrap is usually added. In this step, it is assumed that the amount of scrap (C: 0.18%; Si: 0.25%; Mn: 0.25%; P: 0.03%; S: 0.03%) added to a tonne of molten steel is 200 kg. The total energy consumption of the whole process is −0.16 GJ.

This study highlights the influence of scrap consumption and molten iron temperature on theoretical energy consumption in the steelmaking process, as shown in Figure 7. There is no doubt that the higher the temperature of molten iron, the lower the theoretical energy consumption. Further, it is found that the theoretical energy consumption of the steelmaking process decreases with the increase in the amount of scrap steel added. However, it is worth mentioning that when the input of scrap steel is increased, the consumption of molten iron is reduced, and the energy consumption of the pre-iron system will be significantly reduced, resulting in a reduction in the energy consumption of the whole system. Therefore, increasing the amount of scrap steel and increasing the initial temperature of molten iron into the furnace is beneficial in saving energy.

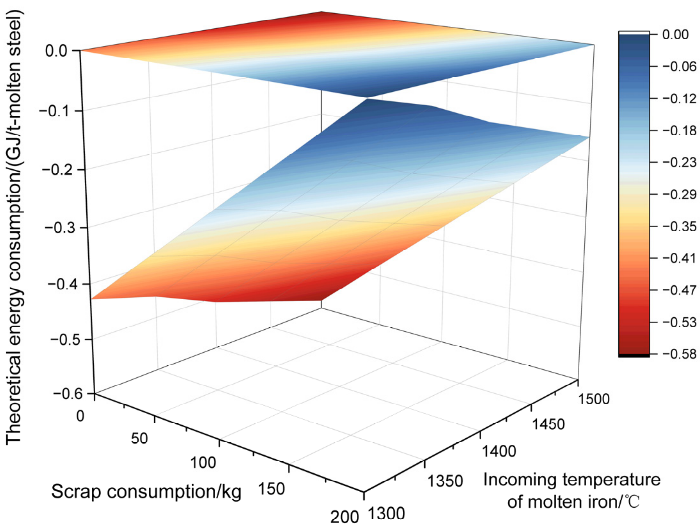



**Figure 7.** Influencing factors of theoretical energy consumption in steelmaking process.

**Table 5.** Theoretical energy consumption of steelmaking process.

| Items | | Product (Molten Steel) Components | | | | | TEC/(GJ/t-Molten Steel) |
|---|---|---|---|---|---|---|---|
| **Steps** | **Hypothesis** | **Fe/%** | **C/%** | **Mn/%** | **P/%** | **S/%** | |
| I | Liquid iron and carbon are considered. | 99.90 | 0.10 | - | - | - | −0.31 |
| II | Si, Mn, P, and S contained in molten iron are considered. | 99.71 | 0.10 | 0.15 | 0.02 | 0.02 | −0.53 |
| III | Scrap is considered. | 99.71 | 0.10 | 0.15 | 0.02 | 0.02 | −0.16 |

### *4.6. Investigating Theoretical Energy Consumption in Rolling Process*

Hot rolling is the process in which the billet is heated by a reheating furnace and then formed into steel products with certain metal properties by a rolling mill. The theoretical energy consumption of the hot rolling process is delineated through a series of steps, as detailed in Table 6. In Step I, consideration is given to the billet at normal temperature. It is assumed that the billet, initially at normal temperature (298 K), is heated to 1473 K in the reheating furnace. The overall energy consumption for this process is calculated to be 0.81 GJ. Moving to Step II, billet oxidation becomes a factor. Within the heating furnace, the billet surface undergoes oxidation, forming $Fe_2O_3$, $Fe_3O_4$, and FeO progressively from the outer to the inner layers. Assuming a surface oxidation rate of 1.5%, the energy consumption for the entire process is determined to be 0.76 GJ.

Through an analysis, it is found that the important factors affecting the theoretical energy consumption of the hot rolling process are the initial temperature and oxidation rate of billet. Figure 8 shows the change in theoretical energy consumption at different initial temperatures and oxidation rates of the billet. It can be seen that the theoretical energy consumption decreases with the increase in initial temperature and oxidation rate of the billet. When the initial temperature of the billet is 1073 K and the oxidation rate of the billet is 3.5%, the theoretical energy consumption of is the lowest in all cases studied, which is 0.07 GJ.

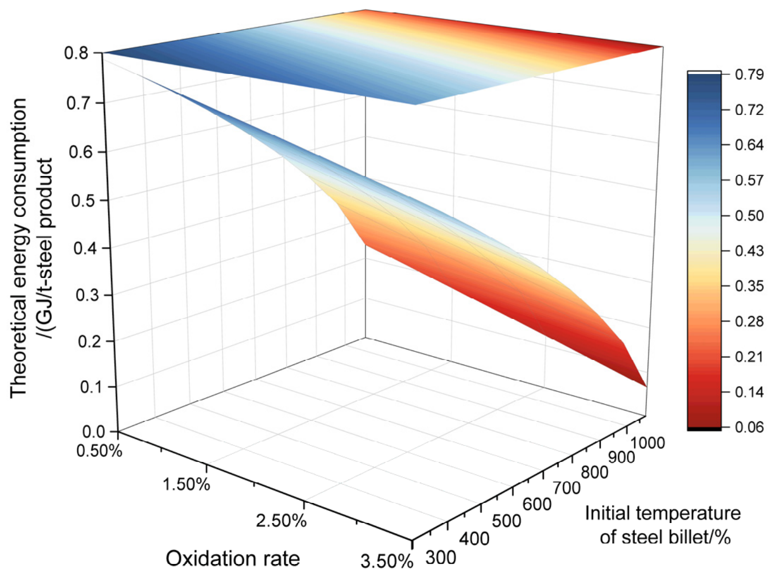



**Figure 8.** Influencing factors of theoretical energy consumption in hot rolling process.

**Table 6.** Theoretical energy consumption of hot rolling process.

| Items | | Product (Steel Product) Components | | | TEC/(GJ/t-Steel Product) |
|---|---|---|---|---|---|
| Steps | Hypothesis | $T_i$/K | $T_r$/K | O | |
| I | Billet with normal temperature is considered. | 298 | 1473 | - | 0.81 |
| II | Billet oxidation is considered. | 298 | 1473 | 1 | 0.76 |

Notes: $T_i$ represents initial temperature; $T_r$ represents rolling temperature; O represents oxidation rate, %.

## 5. Conclusions

The innovative concept of theoretical energy consumption for the ISMP in long-term energy conservation research provides valuable insights into the energy required for iron and steel production, contributing to advancements in energy efficiency. Upon analysis, the theoretical energy consumption for specific processes under selected conditions is as follows: 2.59 GJ for coking, 1.36 GJ for sintering, 1.02 GJ for pelletizing, 8.81 GJ for ironmaking, −0.16 GJ for steelmaking, and 0.76 GJ for hot rolling. Then, this study delves into the influencing factors affecting theoretical energy consumption, using the coking process as an example. It reveals that moisture, volatile, and ash content in coal are detrimental to the theoretical energy consumption of the coking process. Therefore, minimizing these factors during the coking process is imperative for energy conservation. Additionally, this study presents the minimum theoretical energy consumption for each process. Under specified conditions, the minimum theoretical energy consumption for coking, sintering, pelletizing, ironmaking, steelmaking, and hot rolling processes is determined as 2.51 GJ, 0.98 GJ, 0.67 GJ, 8.38 GJ, 0.58 GJ, and 0.07 GJ, respectively.

In this study, a systematic examination of the theoretical energy consumption associated with various products arising from diverse raw materials has been conducted. It is important to note that the analysis is conducted in a step-by-step fashion, excluding considerations for overall losses, such as furnace body loss and combustion loss. A critical avenue for future research lies in transitioning from the theoretical energy consumption framework to a comprehensive exploration of actual energy consumption. It is recommended that future investigations prioritize an in-depth analysis that encompasses not only theoretical aspects but also factors in the practical realities of energy usage. This shift towards assessing actual energy consumption will be instrumental in enhancing the energy utilization efficiency of the ISMP. By addressing both theoretical and practical dimensions, the research can provide a more comprehensive understanding and actionable insights for optimizing energy efficiency within the ISMP.

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## References


1. Zhang, S.; Yi, B.; Guo, F.; Zhu, P. Exploring selected pathways to low and zero $CO_2$ emissions in China's iron and steel industry and their impacts on resources and energy. *J. Clean. Prod.* **2022**, *340*, 130813. [CrossRef]
2. Ren, L.; Zhou, S.; Peng, T.; Ou, X. A review of $CO_2$ emissions reduction technologies and low-carbon development in the iron and steel industry focusing on China. *Renew. Sustain. Energy Rev.* **2021**, *143*, 110846. [CrossRef]
3. World Steel Association. Steel Statistical Yearbook. 2024. Available online: https://www.worldsteel.org/zh/steel-by-topic/statistics/steel-statistical-yearbook.html (accessed on 22 March 2024).
4. Chen, D.; Li, J.; Wang, Z.; Lu, B.; Chen, G. Hierarchical model to find the path reducing $CO_2$ emissions of integrated iron and steel production. *Energy* **2022**, *238*, 124887. [CrossRef]
5. Huang, D.; Dinga, C.D.; Wen, Z.; Razmadze, D. Industrial-environmental management in China's iron and steel industry under multiple objectives and uncertainties. *J. Environ. Manag.* **2022**, *310*, 114785. [CrossRef] [PubMed]
6. Na, H.; Du, T.; Sun, W.; He, J.; Sun, J.; Yuan, Y.; Qiu, Z. Review of evaluation methodologies and influencing factors for energy efficiency of the iron and steel industry. *Int. J. Energy Res.* **2019**, *43*, 5659–5677. [CrossRef]
7. National Bureau of Statistics 2024. National Data. Available online: http://data.stats.gov.cn/search.htm?s=%E7%B2%97%E9%92%A2 (accessed on 1 March 2024).
8. He, K.; Wang, L. A review of energy use and energy-efficient technologies for the iron and steel industry. *Renew. Sustain. Energy Rev.* **2017**, *70*, 1022–1039. [CrossRef]
9. Zhang, Q.; Zhao, X.; Lu, H.; Ni, T.; Li, Y. Waste energy recovery and energy efficiency improvement in China's iron and steel industry. *Appl. Energy* **2017**, *191*, 502–520. [CrossRef]
10. Zhu, C.; Chen, X.; Wu, H.; Zhu, J.; Peng, T.; Lv, J.; Wu, Y. Multi-objective optimization of selective laser melting processes for minimizing energy consumption and maximizing product tensile strength. *Metals* **2022**, *12*, 1782. [CrossRef]
11. Tomažič, S.; Andonovski, G.; Škrjanc, I.; Logar, V. Data-driven modelling and optimization of energy consumption in EAF. *Metals* **2022**, *12*, 816. [CrossRef]
12. Thongjitr, P.; Kowitwarangkul, P.; Pratumwal, Y.; Otarawanna, S. Optimization of Oxygen Injection Conditions with Different Molten Steel Levels in the EAF Refining Process by CFD Simulation. *Metals* **2023**, *13*, 1507. [CrossRef]
13. Feng, H.; Chen, L.; Liu, X.; Xie, Z.; Sun, F. Constructal optimization of a sinter cooling process based on exergy output maximization. *Appl. Therm. Eng.* **2016**, *96*, 161–166. [CrossRef]
14. Liu, Y.; Yang, J.; Wang, J.; Cheng, Z.-L.; Wang, Q.-W. Energy and exergy analysis for waste heat cascade utilization in sinter cooling bed. *Energy* **2014**, *67*, 370–380. [CrossRef]
15. Liu, C.; Xie, Z.; Sun, F.; Chen, L. Exergy analysis and optimization of coking process. *Energy* **2017**, *139*, 694–705. [CrossRef]
16. Liu, X.; Chen, L.; Qin, X.; Sun, F. Exergy loss minimization for a blast furnace with comparative analyses for energy flows and exergy flows. *Energy* **2015**, *93*, 10–19. [CrossRef]
17. Çamdali, Ü.; Tunç, M. Exergy analysis and efficiency in an industrial AC electric ARC furnace. *Appl. Therm. Eng.* **2003**, *23*, 2255–2267. [CrossRef]
18. Kaska, O. Energy and exergy analysis of an organic Rankine for power generation from waste heat recovery in steel industry. *Energy Convers. Manag.* **2014**, *77*, 108–117. [CrossRef]
19. Na, H.; Sun, J.; Qiu, Z.; He, J.; Yuan, Y.; Yan, T.; Du, T. A novel evaluation method for energy efficiency of process industry—A case study of typical iron and steel manufacturing process. *Energy* **2021**, *233*, 121081. [CrossRef]
20. Wu, J.; Wang, R.; Pu, G.; Qi, H. Integrated assessment of exergy, energy and carbon dioxide emissions in an iron and steel industrial network. *Appl. Energy* **2016**, *183*, 430–444. [CrossRef]
21. Fruehan, R.J.; Fortini, O.; Paxton, H.W.; Brindle, R. *Theoretical Minimum Energies to Produce Steel for Selected Conditions*; U.S. Department of Energy Office of Industrial Technologies: Washington, DC, USA, 2000. Available online: https://www1.eere.energy.gov/manufacturing/resources/steel/pdfs/theoretical_minimum_energies.pdf (accessed on 3 March 2024).
22. Martelaro, N. Energy Use in US Steel Manufacturing. Stanford University. 2016. Available online: http://large.stanford.edu/courses/2016/ph240/martelaro1/ (accessed on 3 March 2024).
23. Zhao, X.; Bai, H.; Lu, X.; Shi, Q.; Han, J. A MILP model concerning the optimization of penalty factors for the short-term distribution of byproduct gases produced in the iron and steel making process. *Appl. Energy* **2015**, *148*, 142–158. [CrossRef]
24. Jiang, Z.; Zhang, X.; Jin, P.; Tian, F.; Yang, Y. Energy Saving potential and process optimization of iron and steel manufacturing system. *Int. J. Energy Res.* **2013**, *37*, 2009–2018. [CrossRef]
25. Dinga, C.D.; Wen, Z. Many-objective optimization of energy conservation and emission reduction in China's cement industry. *Appl. Energy* **2021**, *304*, 117714. [CrossRef]
26. Costa, M.M.; Schaeffer, R.; Worrell, E. Exergy accounting of energy and materials flows in steel production systems. *Energy* **2000**, *26*, 363–384. [CrossRef]
27. Sun, W.; Wang, Q.; Zhou, Y.; Wu, J. Material and Energy Flows of the Iron and Steel Industry: Status Quo, Challenges and Perspectives. *Appl. Energy* **2020**, *268*, 114946. [CrossRef]
28. Sun, W.; Wang, Q.; Zheng, Z.; Cai, J. Material-energy-emission nexus in the integrated iron and steel industry. *Energy Convers. Manag.* **2020**, *213*, 112828. [CrossRef]
29. Zhang, H.; Sun, W.; Li, W.; Ma, G. A carbon flow tracing and carbon accounting method for exploring $CO_2$ emissions of the iron and steel industry: An integrated material–energy–carbon hub. *Appl. Energy* **2022**, *308*, 118485. [CrossRef]

30. Zhang, Q.; Wei, Z.; Ma, J.; Qiu, Z.; Du, T. Optimization of energy use with $CO_2$ emission reducing in an integrated iron and steel plant. *Appl. Therm. Eng.* **2019**, *157*, 113635. [CrossRef]
31. Tan, X.; Li, H.; Guo, J.; Gu, B.; Zeng, Y. Energy-saving and emission-reduction technology selection and $CO_2$ emission reduction potential of China's iron and steel industry under energy substitution policy. *J. Clean. Prod.* **2019**, *222*, 823–834. [CrossRef]
32. Na, H.; Sun, J.; Qiu, Z.; Yuan, Y.; Du, T. Optimization of energy efficiency, energy consumption and $CO_2$ emission in typical iron and steel manufacturing process. *Energy* **2022**, *257*, 124822. [CrossRef]
33. Wang, J.; Sun, W. Decomposition of the site-level energy consumption and carbon dioxide emissions of the iron and steel industry. *Environ. Sci. Pollut. Res.* **2024**, *31*, 16511–16529. [CrossRef]
34. Agrawal, A. Technological Advancements in Cokemaking. *Miner. Process. Extr. Metall. Rev.* **2024**. [CrossRef]