Wiley
International Journal of Energy Research
Volume 2025, Article ID 8838411, 21 pages
https://doi.org/10.1155/er/8838411

Research Article

Energy Resource Cost Accounting Method in Iron and Steel Industry Considering Production Process and Multiproduct Effect

Wenwu Ding [1], **Sergio Usón** [2], **and Yan Long** [3]

[1]Key Laboratory of Fluid and Power Machinery, Ministry of Education and Key Laboratory of Fluid Machinery and Engineering, School of Energy and Power Engineering, Xihua University, Chengdu, China
[2]Energaia Research Institute, Department of Mechanical Engineering, University of Zaragoza, Zaragoza, Spain
[3]School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan, China

Correspondence should be addressed to Wenwu Ding; wenwu_ding@sina.com, Sergio Usón; suson@unizar.es, and Yan Long; ly_hust@hust.edu.cn

Received 9 December 2024; Revised 11 August 2025; Accepted 22 August 2025

Academic Editor: Fatemeh Boshagh

The iron and steel industry is a major consumer of energy. Many companies are turning to energy efficiency technologies. Management innovation is also important in increasing efficiency. In this study, we focus on the rational cost accounting of energy medium products in an iron and steel plant. While most of these products are used internally, some of them can be sold to outside users. Therefore, fair and rational cost allocation for these products is crucial for recovering costs and maximizing profits. Unfortunately, there is currently a lack of a fair and rational cost accounting method. To address this issue, we propose a thermoeconomic-based cost accounting method. We calculate the cost of six energy medium products for a model system. The cost of producing steel is found to be 2489.50 ¥/ton, while the costs for producing coke oven gas, converter gas, high-pressure steam (HPS), middle-pressure steam (MPS), low-pressure steam (LPS), and electricity are 2.40 ¥/m^3, 1.79 ¥/m^3, 428 ¥/ton, 371 ¥/ton, 305 ¥/ton, and 1.36 ¥/kWh, respectively. Our analysis indicates that other models may underestimate the cost of energy medium products, which can hinder subplant energy efficiency analysis. Therefore, plant management should reconsider its cost accounting methods and develop a better pricing model.

Keywords: cost allocation; energy medium; iron and steel; thermoeconomic

1. Introduction

China's iron and steel manufacturing process (ISMP) industry, responsible for ~15% of the nation's total CO_2 emissions in 2022 [1], plays a pivotal role in the country's decarbonization efforts. Enhancing the recycling and utilization of waste and by-products will be essential for optimizing resource efficiency and CO_2 reduction, as demonstrated in the battery industry [2–4]. Several methods and models have been proposed in the literature to optimize the utilization of energy medium products. For instance, in [5], a repowering scheme is proposed for better utilization of chemical energy from metallurgical fuel gases. In [6], total site profile pinch analysis is conducted to identify and quantify the potential for energy savings through heat under 300°C. Furthermore, through the integrated implementation of low-carbon, zero-carbon, and negative-emission technologies, the iron and steel industry can progressively realize a sustainable, green, and low-carbon transformation. A comprehensive review of energy efficiency enhancement methodologies in the steel manufacturing sector is presented in [7]. Much research has focused on technical energy efficiency, but the potential for energy efficiency through proper energy management is significant and still largely untapped. Effective structural optimization and managerial innovations are critical for conventional steel mills to achieve significant reductions in energy consumption and CO_2 emissions while improving economic performance indicators [8]. A study of the Swedish iron and steel industry by

Jean-Christian Brunke [9] identified internal economic and behavioral barriers as the biggest obstacles to energy efficiency in the sector, while energy management was found to be the most significant driver of energy efficiency. Proper energy management resulted in a cost-effective energy efficiency potential of 9.7%, which was 2.4% higher than the technical cost-effective energy efficiency potential. Similarly, there is significant potential for management energy efficiency in the Chinese ISMP, as noted by Kavvadias [10]. Nevertheless, insufficient organizational awareness and weak managerial commitment remain substantial barriers to implementing energy efficiency measures in the steel industry [11]. The transition to a circular economy with low-carbon transformation in the iron and steel industry faces significant implementation challenges, primarily stemming from competing objectives among energy efficiency, environmental compliance, and economic performance [12]. Energy costs constitute a primary determinant of the future sustainability performance of ISMP, with high capital expenditures representing a particularly significant barrier to decarbonization [13]. Consequently, the development and implementation of rational energy cost accounting methodologies are critical for facilitating the green transition in this sector.

The iron and steel industry is a complex multifeed multiproduct system that consumes a significant amount of energy. Proper design of this system can result in improved energy efficiency and economic benefits, as shown by a dozen previous works [14–19]. The energy medium, consisting of coal gas, coke, steam, high-temperature water, air, electricity, and other sources, contains considerable thermal and chemical energy that contributes to the stable operation of the plant. In [20, 21], the authors introduce the application of by-product gas and propose a forecast model for gas supply, demand, and surplus. In [22, 23], a MILP model is presented for optimizing the management of by-product gas utilization in an iron and steel plant. In the context of energy medium cost accounting, there is limited published research on the cost allocation of energy medium products in the iron and steel industry. Coal gas and steam, which are produced as by-products in iron and steel plants, are usually priced based on their heating value and the price of natural gas, according to previous studies. Other methods, such as coal-based and opportunity cost-based methods, have also been reported [24]. It should be noted that the pricing of coal, gas, and steam varies in different industries. Since coke oven gas (COG) has a higher exergy and can be utilized in multiple ways, various data on COG can be found in the literature. For instance, in [25], the authors presented the status of COG utilization and introduced several ways to use the surplus COG. In [26], a thermoeconomic analysis was conducted for a proposed combined system using COG and blast furnace gas (BFG), and the cost of COG used was reported as 0.164 $\$/m^3$. This price was determined based on the heating value ratio of COG to natural gas, which is similar to the data presented in [24].

The cost of electricity in iron and steel plants using coal gas is often determined using the heating value ratio of coal gas to natural gas and the market price of natural gas [27]. For example, two plant arrangements were analyzed using exergoeconomic methods, resulting in electricity costs of ~40 and 36 $/MWh [27]. While previous studies assessing combined cycles with COG and BFG derived fuel costs from coal gas heating values and COG-natural gas price ratios [28, 29], their assumption of very low BFG prices may have overstated the profitability of BFG-based power generation. In other investigations, COG was utilized in polygeneration systems with methanol and power production, and its price was found to be 0.05 $\$/m^3$ [30] or 0.8 ¥/m^3 [31, 32], while the price of COG in some iron and steel plants in China was determined based on the heating value and price of natural gas or coal [24]. However, the input fuel cost and actual production process are often not taken into consideration when determining coal gas prices, resulting in generally low prices. However, current methodologies in the literature predominantly rely on heating-value-based approaches, which fail to account for production process characteristics and multi-product synergies. Based on the literature review and analysis above, scientific gaps can be noticed: (1) The existing cost allocation method in ISMP did not consider the production process. (2) The cost of waste flows is not considered. (3) The cost formation is not revealed using previous methods. This study aims to address these critical limitations by developing a comprehensive framework that incorporates both process-specific parameters and by-product interactions.

In an iron and steel plant, coal gas is comprised of COG, BFG, and converter gas, while there are high-pressure steam (HPS), middle-pressure steam (MPS), and low-pressure steam (LPS) systems present as well. Therefore, ensuring a fair and equitable cost allocation method is the focal point of this investigation. There are numerous studies on the subject of cost allocation for energy products, with the most prominent aspects being cost allocation in power-heat combined systems (CHP) and cost distribution in power-water combined systems. Table 1 presents a comparative review of selected representative methodologies. The analysis reveals that thermoeconomic-based approaches offer distinct advantages by simultaneously incorporating production process characteristics, multiproduct interactions, and waste cost accounting.

While both exergy analysis [45] and thermoeconomic methods [46] have been applied to ISMP, these works remain deficient in their treatment of energy medium products cost allocation. This study bridges the existing research gap by developing an integrated thermoeconomic model that comprehensively accounts for (1) input costs and production process, (2) waste stream cost allocation, and (3) cost formation.

In this study, we developed a flow model for an iron and steel plant and used a thermoeconomic model to calculate the unit exergy cost and unit economic cost. Our analysis revealed that the cost of energy medium products may have been underestimated using traditional methods. We propose that the thermoeconomic model used in this study offers a fair and rational approach for cost allocation. This work demonstrates how thermoeconomic modeling enables more comprehensive cost estimation in ISMP by simultaneously accounting for input costs, production process, waste stream cost allocation, and cost formation function.

Table 1: Selected multiproduct cost accounting method.

Method type	Detail production process	Products	Waste consideration	Source
Entropy change ratio approach	Only a turbine process is considered	Power and heat	No	[33]
Btu equivalence method	No	Power and heat	No	[33]
Enthalpy drop method	No	Power and heat	No	[33]
Heat discount method	No	Power and heat	No	[33]
Exergy method	No	Power and heat	No	[33]
Reduced exergy method	Only a turbine process is considered	Power and heat	No	[34]
Cogeneration efficiency method	No	Power and heat	No	[35]
Exergetic cost theory	Yes	Power and heat	No	[36]
Thermoeconomic functional approach	Yes	Power and heat	No	[37]
Specific-cost exergy-costing approach	Yes	Power and heat	No	[38]
Exergy content of final products	Yes	Power and cooling	No	[39]
Unit exergoeconomic cost ratio	Yes	Power and heat	Yes	[40]
Wonergy method	Yes	Power and heat	No	[41]
WEA method	Yes	Power and water	No	[42]
Exergy pro-rating cost allocation	Yes	Power and water	No	[43]
Benefit distribution method	No	Power and water	No	[44]
Thermoeconomic method in this work	Yes	Coal gas, steam, electricity, steel, chemical product	Yes	This work

2. Thermoeconomic Analysis of Model System

Table 1 presents a comparative evaluation of cost accounting methodologies, demonstrating that the proposed framework provides comprehensive coverage of (1) production process parameters, (2) waste stream, (3) energy flow analysis, and (4) nonenergy material flows, which is a significant advancement over existing works that typically address only subsets of these critical dimensions.

2.1. Fundamental of Exergy. Before the introduction of exergy cost, the concept of exergy will be introduced first. Exergy is the maximum theoretical useful work that can be obtained from a flow or system while interacting with the environment. It is composed of physical exergy and chemical exergy, expressed as follows:

$$E_{sys} = E_{sys}^{PH} + E^{CH}. \tag{1}$$

where E_{sys} is the system exergy, E_{sys}^{PH} is the system physical exergy, E^{CH} is the chemical exergy. For a flow, the physical exergy can be calculated by the following:

$$E_{sys}^{PH} = H - H_0 - T_0(S - S_0). \tag{2}$$

Here, H is the enthalpy, H_0 is the enthalpy for the reference state, S is the entropy and S_0 is the reference state entropy, and T_0 is the reference temperature. The chemical exergy in Equation 1 is defined to express the exergy related to the chemical composition difference between a system and the reference environment.

2.2. Symbolic Thermoeconomic Analysis and Cost Formation. With the exergy data for each flow, thermoeconomic analysis can be conducted. The general theory of symbolic exergy analysis [47, 48] and cost formation based on external fuel is described below.

2.2.1. Productive Structure. To perform thermoeconomic analysis, the first step is to define the productive structure, which represents the productive relations among components. A system can be divided into productive and dissipative devices. Productive devices produce useful products while dissipative devices produce waste. Each device has input and output flows. The flows that represent the purpose of the device are called product (P), while the flows required to produce this product are called fuel (F). In this study, all flows are expressed in exergy units and described in Table 2. However, due to irreversibility (I), the exergy value is partially destroyed, which can be represented by the following equation for component i:

$$F_i = P_i + I_i. \tag{3}$$

In addition, the flow between component i and j is represented as E_{ij}. Thus, the fuel and product for the component can be summarized as follows:

Table 2: Flow meaning and its exergy value.

Flow number	Meaning	Exergy (MJ/ton coke)
1	Coal + air + electricity + low-pressure steam	40,539
2	Chemical product	1985
3	Coke dry quenching gas produced low temperature steam	173
4	Coke	30,108
5	Coke oven gas to blast furnace	247
6	Blast furnace gas to coke oven	2964
7	Coke oven gas produced in coke oven	7636
8	Coke oven gas used in coke oven	144
9	Coke oven gas to converter	194
10	Blast furnace gas to converter	66
11	Molten iron	23,517
12	Coal powder + air blast + oxygen + air + nitrogen + low-pressure steam	13,974
13	Electricity form blast furnace	189
14	Low-pressure steam for blast furnace	295
15	Molten steel	21,144
16	Low-pressure steam for converter	204
17	Converter gas to pipe	256
18	Converter gas to environment	256
19	Converter slag + smoke and dust + converter gas emission + slag iron + slopping iron + flue gas + waste water	1576
20	Blast furnace gas to boiler	6752
21	COG	5610
22	COG to environment	1440
23	COG to boiler	1440
24	Flue gas from boiler 1	288
25	Water	0
26	High-pressure steam extracted	72
27	High-pressure steam for turbine	648
28	Work form turbine	346
29	Electricity	329
30	Low-pressure steam extracted	65
31	Middle-pressure steam extracted	194
32	Total high-pressure steam	410
33	Electricity form boiler 2	1541
34	Work from turbine 2	1622
35	Water	0
36	Flue gas from boiler 2	1350
37	High-pressure steam	338
38	High-pressure steam for turbine 2	3038
39	Middle-pressure steam extracted	911
40	Low-pressure steam extracted	304
41	Total middle-pressure steam	498
42	Total low-pressure steam	1040
43	Total electricity	2059
44	Blast furnace gas produced	15,253
45	Blast furnace gas used in blast furnace	4871
46	Steel scrap + alloy + mill scale + calcium oxide + dolomite + fluorite + oxygen + argon + nitrogen + electricity	3354

Table 2: Continued.

Flow number	Meaning	Exergy (MJ/ton coke)
47	Flue gas from pellet	29
48	Concentrate ore+bentonite+steam +electricity	801
49	Ore + solvent + air + coke powder + low-pressure steam + electricity	5767
50	Waste from sinter (return mine + flue gas)	538
51	COG to pellet	697
52	Blast furnace gas to pellet	68
53	Pellet	158
54	Sinter	1209
55	Blast furnace gas in sinter	28
56	COG to sinter	188
57	COG to refining	57
58	COG to continuous casting	273
59	COG to rolling	2955
60	Blast furnace gas to rolling	504
61	Alloy + lime + fluorite + top slag + oxygen + argon + nitrogen + steam + electricity	590
62	Waste flow for refining	157
63	Molten steel	21,186
64	Oxygen + argon + nitrogen + covering slag + steam + electricity	262
65	Waste flow for continuous casting (Mill scale + Steel scrap + other waste)	430
66	Continuous casting billet	19,241
67	Converter gas in rolling	1018
68	Steam + nitrogen + oxygen + hydrogen + electricity	1486
69	Rolling steel product	18,094
70	Waste flow for rolling (steel scrap + mill scale + flue gas + waste water)	1092
71	Flue gas from coking	220
72	Waste from blast furnace (furnace dust + scrap + water + flue gas)	1377
73	Recycled steam to LT steam sinter	77
74	Recycled steam to LT steam rolling	35
75	Flue gas from boiler 1	288
76	Flue gas from boiler 2	1350
77	Waste flow for refining	157
78	Converter slag + smoke and dust + converter gas emission + slag iron + slopping iron + flue gas + waste water	1576
79	Waste flow for continuous casting (mill scale + Steel scrap + other waste)	430
80	Flue gas from coking	220
81	Flue gas from pellet	29
82	Waste from blast furnace (furnace dust + scrap + water + flue gas)	1377
83	Waste from sinter (return mine + flue gas)	538
84	Waste flow from rolling (steel scrap + mill scale + flue gas + waste water)	1092

$$F_i = \sum_{j=0}^{n} E_{ji}, \quad (4)$$

$$P_i = \sum_{j=0}^{n} E_{ij}. \quad (5)$$

The whole elements of E_{ij} are called the fuel-product table. The sum of the row values is the total product for a component. The summation of column elements is the total fuel for this component. In the above equation, component 0 means the environment. Besides, distribution coefficients y_{ij} are defined to describe the proportion of P_j used as the input resource for component i, expressed as follows:

$$y_{ij} = \frac{E_{ji}}{P_j}. \quad (6)$$

Substituting Equation (6) into Equation (4), we get the following:

$$F_i = E_{0i} + \sum_{j=1}^{n} y_{ij} P_j. \quad (7)$$

Equation (7) represented in matrix notation is as follows:

$$F = \mathrm{Fe} + \langle \mathrm{FP} \rangle P. \quad (8)$$

The $\langle \mathrm{FP} \rangle$ matrix contains elements y_{ij}. Fe is a vector containing an external resource into the system. F is a vector for all component fuel, and P is a vector for all component product.

2.2.2. Exergy Cost and Cost Formation. To get flow E_{ij}, a given amount of exergy resources is needed. This amount is its cost and is represented as E^*_{ij}. In a similar way, the cost of fuel is F^* and the cost of product is P^*. For component i, all the cost of F_i is either from the environment or from other components represented as follows:

$$F^*_i = E^*_{0i} + \sum_{j=1}^{n} E^*_{ji}. \quad (9)$$

The quotient between the cost of a flow and its exergy is the unit exergy cost of that flow and is represented by k^*. Assuming that the same productive process has the same unit cost, thus the cost of flows has the same relation as described in Equation (6).

$$y_{ij} = \frac{E^*_{ji}}{P^*_j}. \quad (10)$$

Besides, cost flow from environment is the same as the exergy value itself.

$$E^*_{0i} = E_{0i}. \quad (11)$$

Equation (9) is represented as follows:

$$F^*_i = E_{0i} + \sum_{j=1}^{n} y_{ij} P^*_j. \quad (12)$$

In matrix form, Equation (12) is as follows:

$$F^* = \mathrm{Fe} + \langle \mathrm{FP} \rangle P^*. \quad (13)$$

If there is no dissipative device, then the fuel cost is equal to the product cost, expressed as follows:

$$P^* = F^*. \quad (14)$$

Combining Equation (13) and Equation (14), we get the following:

$$P^* = (U_D - \langle \mathrm{FP} \rangle)^{-1} \mathrm{Fe}. \quad (15)$$

In Equation (15), U_D is the identity matrix. This equation relates the external resource to the component product cost. Sometimes, there are components such as condensers or stacks whose function is to dissipate exergy. These components are called "dissipative devices." When these are present, a third type of flow appears, namely waste flow R. If a device produces waste, its cost should be allocated to the device producing it. The ratio to allocate waste is an open topic. Here, it is applied by using a coefficient ψ that represents the ratio as follows:

$$\psi_{jr} = \frac{R^*_{rj}}{R^*_{r0}}. \quad (16)$$

In Equation (16), R^*_{r0} is the cost of dissipative component r, and R^*_{rj} is the waste cost charged to component j. In matrix notation,

$$R^* = \langle \mathrm{RP} \rangle P^*. \quad (17)$$

The R^* contains elements, meaning the waste cost allocated to each component. $\langle \mathrm{RP} \rangle$ matrix is the matrix containing elements ψ. With waste in the system, the cost balance is as follows:

$$P^* = F^* + R^*. \quad (18)$$

Combining Equation (13) and Equation (17), the full cost formation can be obtained as follows:

$$P^* = (U_D - \langle \mathrm{FP} \rangle - \langle \mathrm{RP} \rangle)^{-1} \mathrm{Fe}, \quad (19)$$

$$B = (U_D - \langle \mathrm{FP} \rangle - \langle \mathrm{RP} \rangle)^{-1}. \quad (20)$$

Table 3: Device number and name.

Number	Device name
1	Coking process
2	Blast furnace process
3	Converter process
4	Blast furnace gas pipeline
5	Coke oven gas pipeline 1
6	Coke oven gas pipeline 2
7	Generator 1
8	Converter gas pipeline
9	Boiler 1
10	Steam turbine 1
11	Generator 2
12	Boiler 2
13	Steam turbine 2
14	High-pressure steam pipeline
15	Middle-pressure steam pipeline
16	Low-pressure steam pipeline
17	Internal grid
18	Pelletizing process
19	Sintering process
20	Refining process
21	Continuous casting
22	Rolling process
23	Flue gas boiler 1
24	Flue gas boiler 2
25	Converter waste discharge
26	Pellet flue gas discharge
27	Sinter waste discharge
28	Refining waste discharge
29	Casting waste discharge
30	Coking flue gas discharge
31	Blast flue gas discharge
32	Rolling waste discharge

Here, the coefficient matrix B is the cost formation coefficient, which directly relates external fuel to component product cost. Using matrix B, the product cost of a certain component can be decomposed into several parts corresponding to different external fuel inputs. Detailed introduction of the methodology can be found in [49].

3. Flow Model for Iron and Steel Plant

The model plant is a general steel mill (BOF route) structure. The whole plant is mainly composed of the coking process (1), pellet process (18), sinter process (19), blast furnace process (2), converter process (3), steel-refining process (20), continuous casting process (21), and steel rolling process (22). All the associated processes/devices are summarized in Table 3. Thirty-two devices are defined here. The flows between these devices are shown in Figure 1. The flow diagram of the entire plant structure is presented in Figure 1, which illustrates the complex relationships between different sub-processes. In addition to the main steel production process (device 1, 2, 3, 18, 19, 20, 21, 22), the system owns electricity production part (device 7, 9, 10, 11, 12, 13, 17), gas pipeline part (device 5, 6, 8, 14, 15, 16), and waste discharge part (device 25–32). The diagram consists of 84 flows that are connected between 32 devices. The complex flow interactions pose a significant challenge in conducting cost allocation for certain product flows. To address this issue, a cost formation analysis is needed to determine how different processes contribute to the target process. For a better understanding of the plant structure, Figure 2 is further divided into four parts: Figure 2A–D. Figure 2A depicts the pellet and sinter process. Figure 2B illustrates the coking process, blast furnace process, and converter process, which are the coal gas production site and molten iron production site. Figure 2C shows the process of steam and electricity production, which typically involves boiler, turbine, and generator processes. Finally, Figure 2D describes how molten iron is transformed into rolling steel through refining, continuous casting, and rolling processes. The meaning of each flow is presented in Table 2.

The present study is focused on the energy medium products in an iron and steel plant. The COG is generated during the coking process and serves as an input in various other processes such as blast furnace, converter, pelleting, sintering, refining, continuous casting, and rolling. The residual COG can either be utilized for steam generation or can be sold to external users. The BFG is produced during the blast furnace process and is employed as an input in the coking process, blast furnace process, converter process, pelleting process, sinter process, and rolling process. The remaining gas is utilized for steam production in the boiler. The converter gas, generated during the converter process, is utilized in the rolling process, and any unused gas is sent to external users. In the flow model presented in Figure 1, the remaining BFG is directed toward the boiler for steam production. On the other hand, the remaining COG and converter gas are sent to external users through flow 18 and flow 22, respectively. The primary product of the plant is steel, which is produced after the rolling process, represented by flow 69. It should be noted that there are multiple steel products in reality, but this study uses a single flow to represent all of them, and thus, the associated data with the steel product pertain to the average data obtained from the rolling process.

The HPS is generated from a boiler, while the MPS is extracted from a steam turbine. The LPS is derived from various sources, including waste heat from the coking process, blast furnace process, and converter process, as well as steam after the steam turbine. Although information on the producers and consumers of coal gas was obtained from the literature, detailed data on steam consumers are unavailable. This is due to a lack of detailed records released regarding how different types of steam are consumed. In iron and steel plants, the steam network is extensive and extends to almost every production site. Some sub-plants use more than one type of steam, but it is unclear how each type of steam is consumed, and they only have total steam consumption data. Therefore, in the flow model, the steam production site is evident, but the steam consumer is not connected to the steam network. A more detailed flow model should be developed in the future

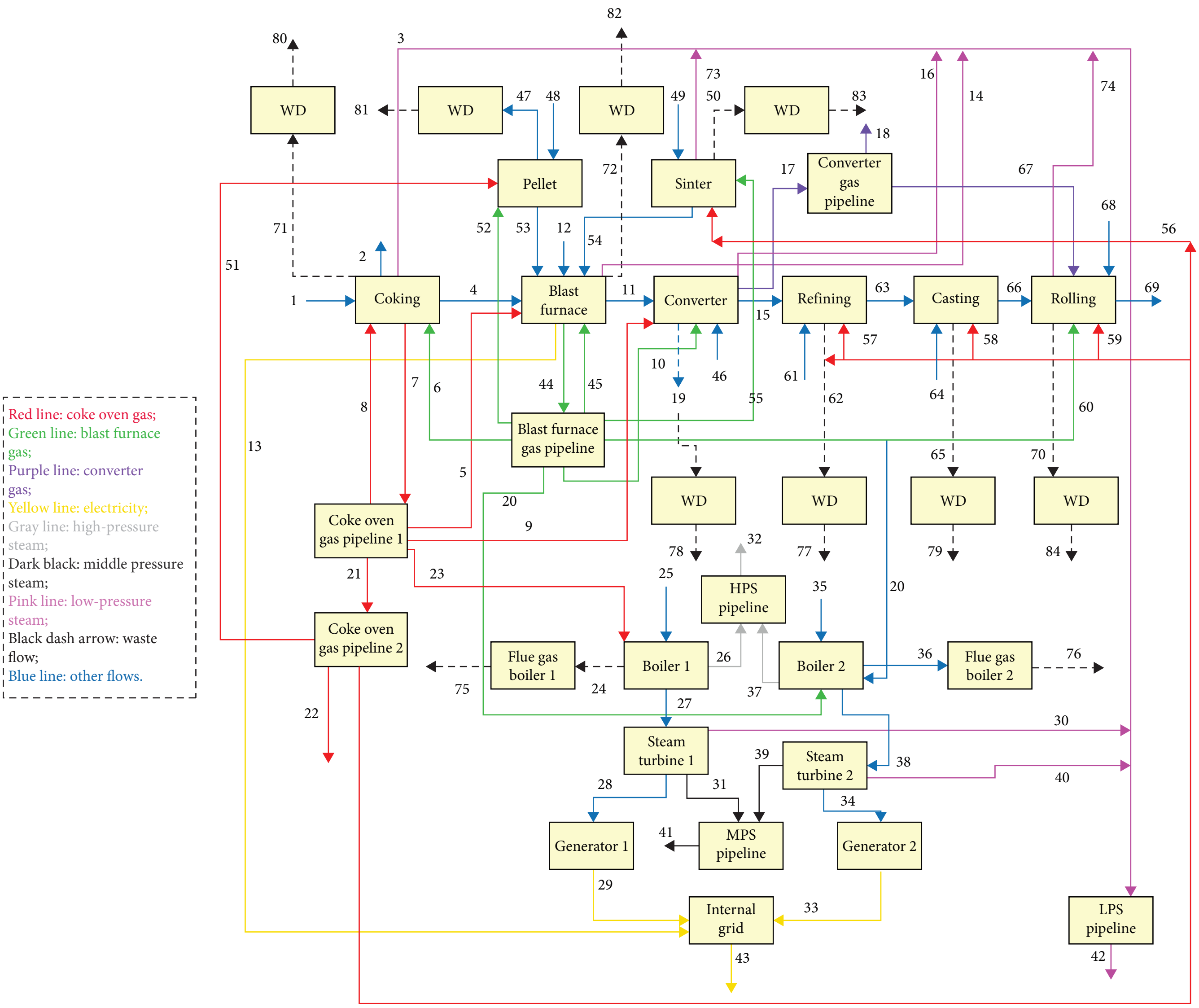

FIGURE 1: Flow model for a whole iron and steel plant. Thirty-two devices represented as box are connected with each other by different flows (84 arrow lines). WD stands for waste discharge device. Nine flows in different colors stand for 8 different energy medium product flows and 1 waste flow. Other flows in blue represent all other flows except the 9 flows mentioned before.

to further illustrate how steam is distributed throughout the system.

In this model system, electricity is generated by two generators as well as the blast furnace. A detailed explanation of the 84 flows in the system can be found in Table 2. It is important to note that a single flow in the table can represent multiple substances, thus reducing the overall number of flows required. Due to the multiple sources of steam and electricity, the calculated cost for these media represents an average cost.

4. Flow Exergy Data and Exergy Analysis

Accessing and publishing the latest productive data can be challenging, as such data are often considered to be a corporate secret. In the present study, the exergy data for the iron and steel plant were obtained from a master thesis by Lang [50]. However, this thesis only provides data for individual sub-processes, and thus, assumptions are required to connect these sub-processes together.

- Assuming that the demand for coke in the blast furnace process is exactly met by the coke produced in the coking process, and the molten iron demand in the converter process is perfectly satisfied by the molten iron produced in the blast furnace process. Additionally, the pellet and sinter can satisfy the demand in the blast furnace process; the molten steel from the converter can meet the demand in the refining process, and the steel after refining can provide the exact need in the continuous casting process. Moreover, the continuous casting billet produced in the continuous casting process meets the demand in the rolling process. Based on these assumptions, it is inferred that 1 ton of

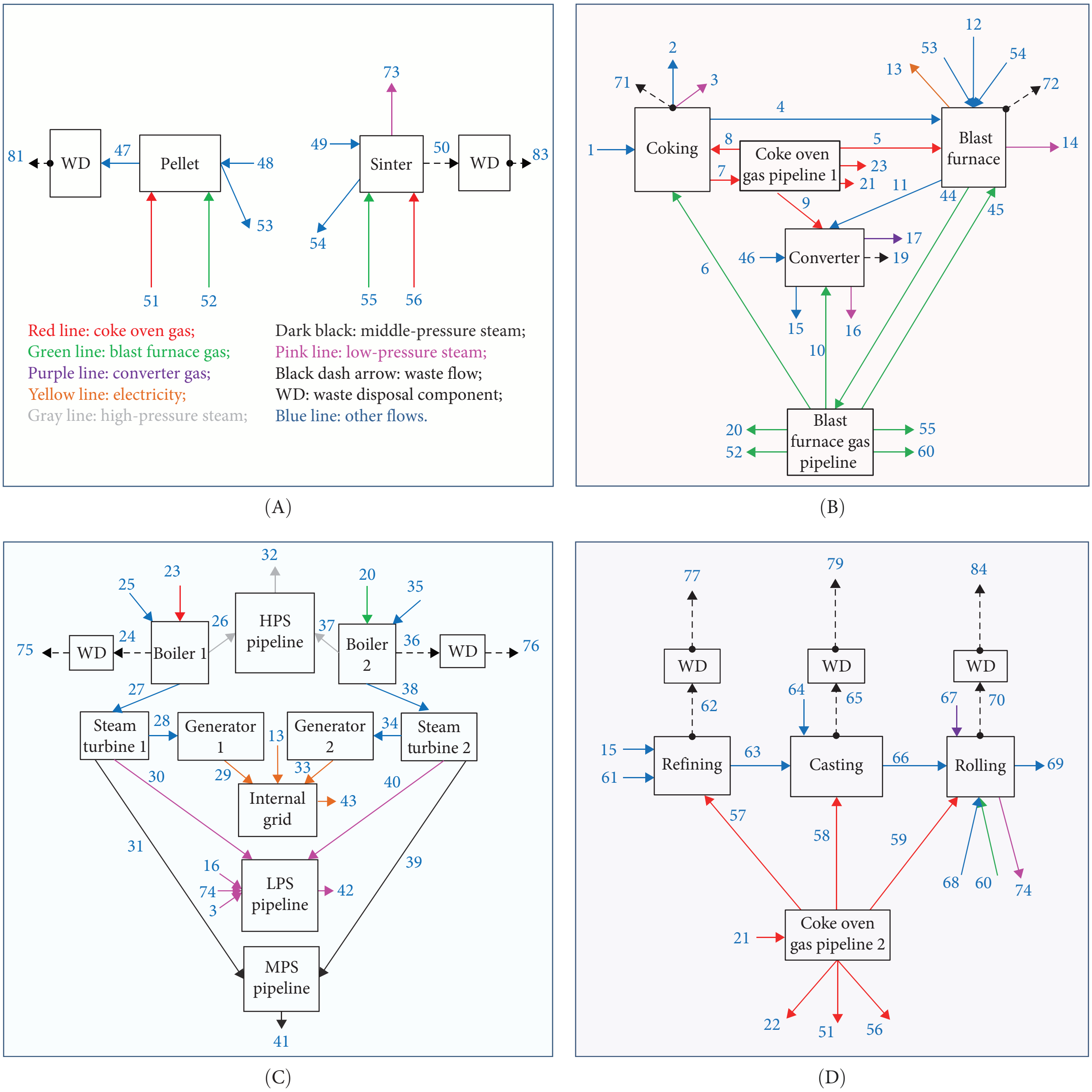

FIGURE 2: Reorganized flow model plotted into four parts: (A) pellet and sinter process; (B) coking, blast furnace, and converter process; (C) steam and electricity production; (D) refining, continuous casting and rolling process.

coke can produce 2.668 tons of molten iron and 2.726 tons of molten steel. Additionally, the entire plant produces 1.25 tons of pellets, 2.96 tons of sinter, 2.80 tons of refining molten steel, 2.74 tons of continuous casting billet, and 2.62 tons of rolling steel products. Using these ratios, the exergy value for each process can be determined. The detailed calculations for these ratios are listed in the Appendix.

- The exergy information for the flows subsequent to the boiler and steam turbine remains undetermined. In order to estimate these values, certain initial parameters are required, including: (i) 50% of the excess COG is directed to the boiler while the remaining 50% is conveyed through the COG pipeline 2; (ii) all of the BFG is directed to the boiler; (iii) converter gas is considered as system output; (iv) both boilers have an exergy efficiency of 50% and a flue gas exergy loss efficiency of 20%, meaning that the flue gas exergy is equivalent to 20% of the input fuel flow for both boilers; (v) 10% of the total steam produced is conveyed through the HPS pipeline, while the remaining steam is directed to the steam turbine; (vi) for both steam turbines, the exergy efficiency is 89%, and 23% of the input exergy is extracted as (MPS), while 17% of the input steam exergy is directed to the LPS pipeline; and (vii) the exergy efficiency of the generator is 95%.

Table 2 presents a summary of the exergy data (per ton coke) for all flows. Flow 24 through flow 43 are calculated using the data for the boiler, turbine, and generator provided earlier. The remaining flow data have been reorganized using the ratios provided above. The original data and the methodology for calculating the unknown data are presented in Tables A1 and A2.

In general, fuels correspond to inputs, while products correspond to outputs. However, this is not always the case, such as in a turbine or heat exchanger. For the purposes of this study, input flows are considered as fuel flows, while output flows are regarded as product flows, except in the case of steam turbine 1 and steam turbine 2. In these cases, the fuel of the steam turbine is determined as the difference between the input and output steam, while the product is the work produced. Table 4 displays the fuel and product table for each device. Each column represents the fuel input for a certain device, while each row displays the product components for each device. For example, device 1 (coking) has a total fuel input of 43,647 MJ (40,539 MJ is from device 0, namely the environment, 2964 MJ from device 4, 144 MJ from device 5). Similarly, device 1 produces in total 40,120 MJ product (1985 MJ goes to device 0, 30,108 MJ goes to device 2, 7636 MJ to device 5, 173 MJ to device 16, 220 MJ to device 30).

In the model plant, all waste is discharged directly into the environment, necessitating several waste dischargers that are classified as dissipative devices. All other devices are considered productive devices. It should be noted that waste flows also consume external input as they are generated during the production of certain products. In this study, the cost of waste is allocated to the device responsible for producing it. The $\langle \mathrm{RP} \rangle$ matrix is utilized to allocate waste to the corresponding device. RP (1, 30), RP (2, 31), RP (3, 25), RP (9, 23), RP (12, 24), RP (18, 26), RP (19, 27), RP (20, 28), RP (21, 29), and RP (22, 32) all have value of 1 and 0 otherwise. Failure to account for waste cost allocation leads to an underestimation of the product cost. Table 5 presents the product unit exergy cost for each component and the cost formation using matrix B and external fuel Fe. The product unit exergy value (MJ/MJ) is obtained by dividing the total exergy needed (from different external input sources) to produce this flow by the product exergy value.

5. Product Cost Calculation

Figure 1 shows the interrelationship between different devices, but the quantity of one device contributing to another remains to be calculated. Table 5 displays the resulting data for the product exergy cost of each device and its formation based on eight processes with external input. The cost formation is achieved by multiplying matrix B with external input from the eight major devices. For instance, the cost of coke oven products per MJ can be decomposed into contributions from 1.09 MJ coking itself, 0.033 MJ from blast furnace, 0.002 MJ from pellet process, and 0.013 MJ from sinter process. The product cost of other process can also be decomposed based on the different external fuel inputs used in each process. The most complex product cost formation occurs in the rolling process. The cost of rolling steel products per MJ is composed of 1.507 MJ from the coking process, 0.576 MJ from the blast furnace process, 0.181 MJ from the converter process, 0.033 MJ from the pellet process, 0.223 MJ from the sinter process, 0.033 MJ from the refining process, 0.014 MJ from the casting process, and 0.082 MJ from rolling itself. This cost formation highlights the interconnections of all system processes. This interrelationship is difficult to demonstrate using only simple input–output balance models. The cost formation here is valuable for cost accounting between sub-processes. Figures 3–6 further illustrate the unit exergy cost for useful products of the plant based on external input of eight processes. The unit exergy cost also reveals the amount of additional input required to produce one unit of product. Furthermore, the cost formation analysis dissects the cost, indicating the source of the additional resource consumption.

Figure 3 illustrates that the pelletizing process has the highest product unit exergy cost (10.7 MJ/MJ) of all productive devices in the model plant, indicating a significant amount of external resource consumption per unit product. Specifically, the extra fuel required for the pellet process is mainly sourced from the coking process (5.2 MJ/MJ) and the pellet process itself (5.1 MJ/MJ), while the unit exergy cost (4.7 MJ/MJ) of sinter is also high, with external resources required predominantly sourced from the sinter process (4.5 MJ/MJ).

Figure 4 presents the unit exergy cost for BFG and COG. The bar corresponding to COG indicates that the fuel input is mainly derived from the coking process itself. The unit product cost (1.63 MJ/MJ) generated from the blast furnace is mainly from the coking process (0.99 MJ/MJ), blast furnace (0.44 MJ/MJ), and sinter process (0.17 MJ/MJ). The unit exergy cost for the converter product (1.86 MJ/MJ) is mainly derived from the coking process (1.05 MJ/MJ), blast furnace (0.46 MJ/MJ), converter (0.15 MJ/MJ), and sinter process (0.18 MJ/MJ), with a minor contribution from the pellet process (0.03 MJ/MJ). This analysis highlights the significant contribution of the coking process to the production of coal gas.

Figure 5 reveals that the unit exergy cost of boiler 2 (in total 3.26 MJ/MJ, 1.99 MJ/MJ sourced from coking, 0.88 MJ/MJ from blast furnace, 0.05 MJ/MJ from pellet process, 0.34 MJ/MJ from sinter process), which uses BFG, is higher than that of boiler 1 (in total 2.28 MJ/MJ, 2.19 MJ/MJ sourced from coking, 0.07 MJ/MJ from blast furnace, 0.004 MJ/MJ from pellet process, 0025 MJ/MJ from sinter process), which uses COG. Similarly, the unit exergy cost of generator 2 (3.85 MJ/MJ) is higher than that of generator 1 (2.7 MJ/MJ). The higher cost of boiler 2 and generator 2 is mainly due to not only distinct resource consumption from blast furnace but also distinct part from coking process. The unit cost of electricity produced by generator 1 is mainly from coking fuel (2.59 MJ/MJ), whereas the cost of electricity produced by generator 2 is mainly from coking fuel (2.36 MJ/MJ), followed by blast furnace (1.03 MJ/MJ), sinter process (0.4 MJ/MJ), and a minor portion from pellet process (0.06 MJ/MJ). These findings

Table 4: Fuel product table.

P/F	F0	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17	F18	F19	F20	F21	F22	F23	F24	F25	F26	F27	F28	F29	F30	F31	F32	Total
P0	0	40,539	13,974	3354	0	0	0	0	0	0	0	0	0	0	0	0	0	0	801	5767	590	262	1486	0	0	0	0	0	0	0	0	0	0	66,773
P1	1985	0	30,108	0	0	7636	0	0	0	0	0	0	0	0	0	0	173	0	0	0	0	0	0	0	0	0	0	0	0	0	220	0	0	40,120
P2	0	0	0	23,517	15,253	0	0	0	0	0	0	0	0	0	0	0	295	189	0	0	0	0	0	0	0	0	0	0	0	0	0	1377	0	40,631
P3	0	0	0	0	0	0	0	0	256	0	0	0	0	0	0	0	204	0	0	0	21,144	0	1018	0	0	1576	0	0	0	0	0	0	0	24,198
P4	0	2964	4871	66	0	0	0	0	0	0	0	0	6752	0	0	0	0	0	68	28	0	0	504	0	0	0	0	0	0	0	0	0	0	15,253
P5	0	144	247	194	0	0	5610	0	0	1440	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7636
P6	1440	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	697	188	57	273	2955	0	0	0	0	0	0	0	0	0	0	5610
P7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	329	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	329
P8	256	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	256
P9	0	0	0	0	0	0	0	0	0	0	389	0	0	0	72	194	65	0	0	0	0	0	0	288	0	0	0	0	0	0	0	0	0	1008
P10	0	0	0	0	0	0	0	346	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	346
P11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1541	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1541
P12	0	0	0	0	0	0	0	0	0	0	0	0	0	1823	338	911	304	0	0	0	0	0	0	0	1350	0	0	0	0	0	0	0	0	4726
P13	0	0	0	0	0	0	0	0	0	0	0	1622	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1622
P14	410	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	410
P15	498	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	498
P16	1040	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1040
P17	2059	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2059
P18	0	0	158	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	29	0	0	0	0	0	0	187
P19	0	0	1209	0	0	0	0	0	0	0	0	0	0	0	0	0	77	0	0	0	0	0	0	0	0	0	0	538	0	0	0	0	0	1825
P20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	21,186	0	0	0	0	0	0	157	0	0	0	0	21,343
P21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	19,241	0	0	0	0	0	0	430	0	0	0	19,671
P22	18,094	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1092	19,221
P23	288	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	288
P24	1350	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1350
P25	1576	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1576
P26	29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	29
P27	538	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	538
P28	157	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	157
P29	430	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	430
P30	220	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	220
P31	1377	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1377
P32	1092	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1092
Total	32,840	43,647	50,568	27,131	15,253	7636	5610	346	256	1440	389	1622	6752	1823	410	1106	1153	2059	1566	5983	21,791	21,721	25,204	288	1350	1576	29	538	157	430	220	1377	1092	—

Note: F stands for fuel and P stands for product, index 1–32 represents devices number, which is listed in Table 3, index 0 represents environment.

Table 5: Product unit exergy cost (MJ/MJ) and cost formation based on external input of (coking, blast furnace, converter, pellet, sinter, refining, casting, and rolling).

Device	Coking cost	Blast furnace cost	Converter cost	Pellet cost	Sinter cost	Refining cost	Casting cost	Rolling cost	Total
Coke oven	1.094	0.033	0.000	0.002	0.013	0.000	0.000	0.000	1.141
Blast furnace	0.996	0.437	0.000	0.025	0.169	0.000	0.000	0.000	1.628
Converter furnace	1.048	0.456	0.148	0.026	0.177	0.000	0.000	0.000	1.855
BFG pipe	0.996	0.437	0.000	0.025	0.169	0.000	0.000	0.000	1.628
COG pipe	1.094	0.033	0.000	0.002	0.013	0.000	0.000	0.000	1.141
COG pipe 2	1.094	0.033	0.000	0.002	0.013	0.000	0.000	0.000	1.141
Generator 1	2.589	0.076	0.000	0.004	0.030	0.000	0.000	0.000	2.699
Converter gas pipe	1.043	0.458	0.148	0.026	0.175	0.000	0.000	0.000	1.851
Boiler 1	2.187	0.065	0.000	0.004	0.025	0.000	0.000	0.000	2.281
Steam turbine 1	2.460	0.073	0.000	0.004	0.028	0.000	0.000	0.000	2.564
Generator 2	2.357	1.034	0.000	0.059	0.401	0.000	0.000	0.000	3.851
Boiler 2	1.993	0.874	0.000	0.050	0.339	0.000	0.000	0.000	3.256
Steam turbine 2	2.239	0.983	0.000	0.056	0.381	0.000	0.000	0.000	3.658
High-pressure steam pipe	2.029	0.734	0.000	0.042	0.284	0.000	0.000	0.000	3.089
Middle-pressure pipe	2.583	0.932	0.000	0.053	0.361	0.000	0.000	0.000	3.929
Low-pressure pipe	1.564	0.545	0.028	0.031	0.477	0.001	0.000	0.002	2.649
Electricity grid	2.258	0.823	0.000	0.047	0.319	0.000	0.000	0.000	3.447
Pellet process	5.249	0.329	0.000	5.089	0.130	0.000	0.000	0.000	10.797
Sinter	0.182	0.015	0.000	0.001	4.487	0.000	0.000	0.000	4.685
Refining	1.049	0.455	0.148	0.026	0.176	0.028	0.000	0.000	1.883
Continuous casting	1.171	0.502	0.163	0.029	0.195	0.031	0.014	0.000	2.103
Rolling	1.507	0.576	0.181	0.033	0.223	0.033	0.014	0.082	2.649
Flue gas boiler 1	2.181	0.063	0.000	0.004	0.026	0.000	0.000	0.000	2.274
Flue gas boiler 2	1.993	0.874	0.000	0.050	0.339	0.000	0.000	0.000	3.257
Converter waste discharge	1.047	0.456	0.148	0.026	0.177	0.000	0.000	0.000	1.853
Pellet flue gas discharge	5.388	0.337	0.000	5.158	0.131	0.000	0.000	0.000	11.014
Sinter waste discharge	0.181	0.014	0.000	0.001	4.485	0.000	0.000	0.000	4.680
Refining waste discharge	1.059	0.454	0.147	0.026	0.176	0.028	0.000	0.000	1.890
Casting waste discharge	1.169	0.500	0.163	0.029	0.194	0.031	0.014	0.000	2.099
Coking flue gas discharge	1.089	0.033	0.000	0.002	0.013	0.000	0.000	0.000	1.136
Blast flue gas discharge	0.995	0.437	0.000	0.025	0.170	0.000	0.000	0.000	1.627
Rolling waste discharge	1.507	0.576	0.181	0.033	0.223	0.033	0.014	0.082	2.649

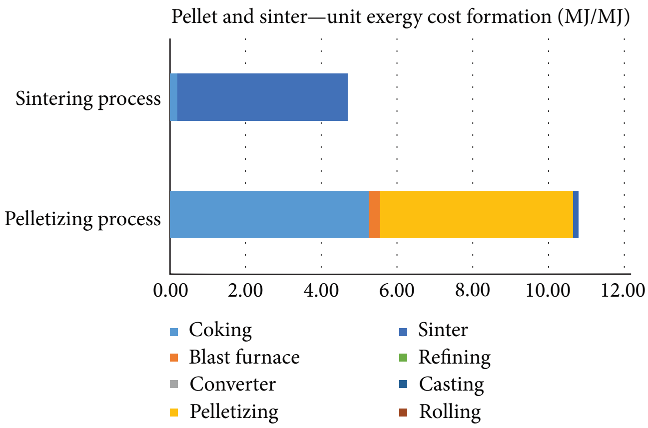

FIGURE 3: Pellet and sinter unit exergy cost decomposition.

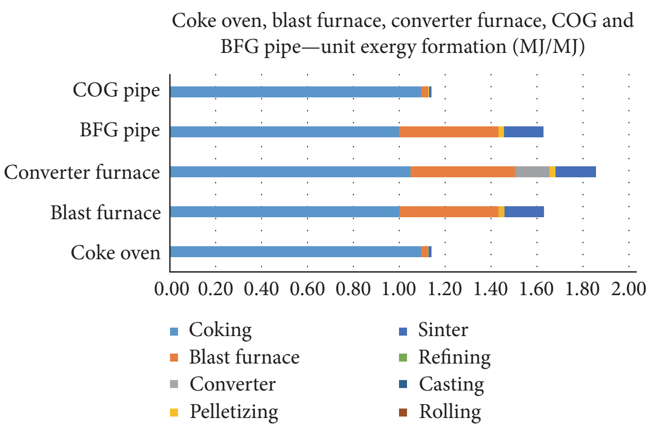

FIGURE 4: Coal gas and molten iron production site-unit exergy cost formation.

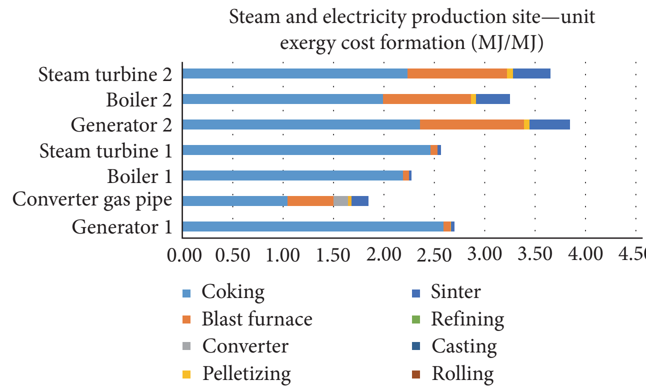

FIGURE 5: Steam and electricity production site-unit exergy cost formation.

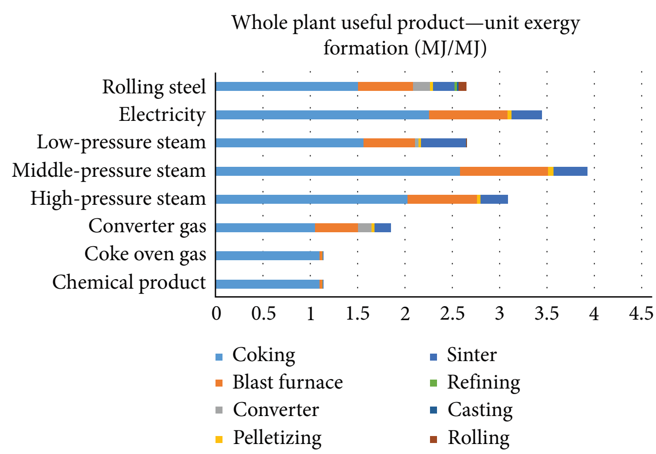

FIGURE 6: Comparison of unit exergy cost for the whole plant useful products (MJ/MJ).

suggest that the cost of electricity would be severely underestimated if the contribution from, for example, the coking process were ignored.

Figure 6 displays the unit exergy cost of the useful product for the entire plant. The results indicate that external resource of coking contributes the largest part to both electricity and steam production, followed by blast furnace and sinter process, with a minor contribution from pellet process. Interestingly, the unit exergy cost of MPS is higher than that of HPS, suggesting that higher heating value does not always translate to higher exergy cost. It is important to note that production costs are process dependent, as illustrated by the unit exergy cost of COG and converter gas. While COG has a higher heating value, the unit exergy cost of converter gas is higher, at 1.85 unit exergy per unit, compared to COG at 1.14 unit exergy per unit product. One unit of HPS costs 3.09 unit exergy, one unit of MPS costs 3.93 unit exergy, and one unit of LPS costs 2.65 unit exergy. The average unit exergy cost of electricity is 3.45 unit exergy per unit. Despite MPS having a lower exergy per volume, it has the largest unit exergy cost compared to other energy mediums. The main reason, as illustrated by the cost formation, is not only external resource consumption in the production site itself but also a large part of external resource consumption from other production sites.

In order to connect external fuel and product cost, matrix B is utilized. It is important to note that, unlike exergy cost calculation, the Fe vector utilized for product cost calculation is in monetary units (¥) and redefined as Fem. Thus, the resulting product cost is also in monetary units. The input and output flows of the model plant are described in Figure 1, and a new flow, designated as flow 85, has been added to account for the cost of manpower and capital (more details in Table A2). The known cost data are presented in Table 6, and are sourced from [50], with the exception of the cost data for flow 85, which is sourced from [51]. It should be noted that the cost value for flow 85 represents an average of four types of steel products (plate and thick plate, hot strip, wire stock, and steel bar) and is not an element of the Fem vector. As the manpower and capital cost distribution among components is not known, the distribution of this cost is done approximately by allocating evenly to each product. The original data and reorganized data for the Fem vector can be found in Appendix A.

Using the matrix B and the available cost data as described earlier, the economic cost formation can be performed in a manner similar to the exergy cost formation. In this case, economic external fuel data (Fem) are utilized instead of exergy external fuel. The results of the economic cost

TABLE 6: Summarized initial known flow cost data.

Input flow number	Input cost (¥)
1	1428.7
12	592.16
25	0
35	0
46	1156.61
48	953.21
49	2128.09
61	143.92
64	66
68	235.55
85	2333.52
Total	8878.115

formation are presented in Table 7. The remaining COG's cost per ton of steel consists of 83 ¥ from coking, 3 ¥ from blast furnace process, 5 ¥ from pellet process, and 10 ¥ from sinter process. The cost of converter gas is more complex. It comprises of 4 ¥ from coking, 2 ¥ from blast furnace, 5 ¥ from itself, 3 ¥ from pellet, and 6 ¥ from sinter process. Remarkably, the major cost associated with the three types of steam is found to be from the sinter process. This can be attributed to the fact that BFG, which is the primary fuel of steam, is produced in the blast furnace process, with its major economic input coming from the sinter process. Sinter is produced through a process that uses fuel primarily from coking. However, the most significant economic contribution comes from an external input in the sintering process known as flow 49. The analysis reveals that nonenergy flows, particularly those with high costs, significantly influence the economic evaluation of energy flows. The cost of electricity is mainly attributed to the sinter process (93 ¥), and 63 ¥ from coking, 28 ¥ from blast furnace, and 44 ¥ from pellet process.

6. Product Cost Analysis

In practice, the price of coal gas is typically expressed in units of ¥/m^3, while the price of steam is expressed in units of ¥/ton, and the price of electricity is expressed in units of ¥/kWh. To convert the exergy-based cost data into these different units, appropriate exergy values must be used. Specifically, the exergy value of COG is 17.5 MJ/m^3, while the exergy of converter gas is 6.08 MJ/m^3. The exergy data for steam were calculated using the software EES, and the steam data were obtained from [52]. The exergy values for HPS, MPS, and LPS were found to be 1230 kJ/kg, 886.7 kJ/kg, and 778.7 kJ/kg, respectively. After converting the units, the cost data for all plant products can be summarized, as shown in Table 8. The cost of chemical products remains in units of yuan per MJ, as it is difficult to convert it to ton or m^3. The chemical products consist of tar, benzene, and ammonia. The exergy of rolled steel is 6609.34 MJ/t.

The flow 85, which represents the cost of manpower and capital, is distributed evenly among all the products. Therefore, an additional exergy cost is added to the original exergy cost. The total product exergy is 25791.84 MJ, and the cost of flow 85 is 2333.52 ¥. As a result, an extra 0.09048 ¥/MJ is added to the previous unit monetary exergy cost. The original unit exergy cost is calculated as $B \times \mathrm{Fem}/P$, where P is the total component product exergy and Fem is the external vector in monetary value. The total unit exergy cost is illustrated in Figure 7.

The unit exergy cost in monetary unit is presented in Figure 7, which is decomposed to show the cost breakdown. The allocation of manpower and capital cost to each product evenly leads to it playing the same role in all products. The cost of chemical products and COG is mainly from manpower and capital, as well as the coking process, which is also related to coal cost. For the other products, coal cost still plays a significant role, but the largest contribution is from the sinter process. The unit cost of LPS is lower than that of MPS. Moreover, the unit cost of MPS is higher than that of HPS, indicating that cost allocation considering only heating value or exergy per volume can sometimes lead to a lower cost compared to calculations considering the entire process. Electricity is primarily produced using BFG, but its cost mainly comes from the sinter fuel cost, manpower and capital, coal cost, pellet process fuel, and blast furnace process fuel. This implies that cost accounting for electricity without a global picture may potentially lead to a lower cost. The main product, rolling steel, mainly incurs cost from sinter fuel, converter fuel, coking fuel, and pellet fuel. The input in the rolling process only contributes a minor part. In short, the cost accounting method without considering production process and multiproduct effect can lead to an underestimation of real cost.

The pricing strategy for by-product gas in iron and steel plants is a complex issue, given the substantial variation in prices for the same gas across different plants. Zhu and He [24] presented three pricing approaches: method 1, which considers the heating value and price of natural gas; method 2, which is based on the heating value and price of coal; and method 3, which accounts for the opportunity cost, that is, the profit from electricity generated by the by-product gas. The prices obtained using these three methods, as well as the costs obtained in this study, are summarized in Table 9.

In Table 9, it can be observed that the price of by-product gas obtained through method 4 (utilized in this study) is considerably higher compared to the other cost data. This can be attributed to the fact that different systems may exhibit distinct exergy costs, and therefore, the cost in other systems may differ from that obtained through method 1, which provides a price for all scenarios only if the heating value remains the same. Nevertheless, method 2 and method 3 display significant deviations when compared to the cost estimated through method 4. It is common to obtain varying costs for different production systems, and the price should be determined based on the cost data. Hence, methods 1–3 only account for the difference in product but disregard the differences in the production process. The actual cost should take into consideration the production process as well. The observed higher cost of coal gas in the analysis of the whole system could be attributed to several other factors. First, it could be due to

Table 7: Economic cost formation for the whole model plant based on external input (per ton of steel).

Device	Coking	Blast furnace	Converter	Pellet	Sinter	Refining	Casting	Rolling	Total (¥)
Coke oven	590	21	0	34	71	0	0	0	717
Blast furnace	545	287	0	463	970	0	0	0	2264
Converter furnace	341	179	472	287	603	0	0	0	1882
BFG pipe	204	108	0	174	364	0	0	0	850
COG pipe	112	4	0	6	14	0	0	0	136
COG pipe 2	83	3	0	5	10	0	0	0	100
Generator 1	11	0	0	1	1	0	0	0	14
Converter gas pipe	4	2	5	3	6	0	0	0	20
Boiler 1	30	1	0	2	4	0	0	0	36
Steam turbine 1	11	0	0	1	1	0	0	0	14
Generator 2	49	26	0	42	87	0	0	0	203
Boiler 2	127	67	0	108	226	0	0	0	527
Steam turbine 2	49	26	0	42	87	0	0	0	203
High-pressure steam pipe	11	5	0	8	16	0	0	0	40
Middle-pressure pipe	23	10	0	16	34	0	0	0	83
Low-pressure pipe	27	11	5	18	87	0	0	0	150
Electricity grid	63	28	0	44	93	0	0	0	228
Pellet process	13	1	0	432	3	0	0	0	450
Sinter process	4	0	0	1	1153	0	0	0	1159
Refining process	301	157	416	253	531	55	0	0	1713
Continuous casting	310	160	422	257	539	56	26	0	1769
Rolling process	390	179	459	288	604	58	27	95	2100
Flue gas boiler 1	8	0	0	0	1	0	0	0	10
Flue gas boiler 2	36	19	0	31	64	0	0	0	151
Converter waste discharge	22	12	31	19	39	0	0	0	123
Pellet flue gas discharge	2	0	0	67	1	0	0	0	70
Sinter waste discharge	1	0	0	0	340	0	0	0	342
Refining waste discharge	2	1	3	2	4	0	0	0	13
Casting waste discharge	7	3	9	6	12	1	1	0	39
Coking flue gas discharge	3	0	0	0	0	0	0	0	4
Blast flue gas discharge	18	10	0	16	33	0	0	0	77
Rolling waste discharge	22	10	26	16	34	3	2	5	119

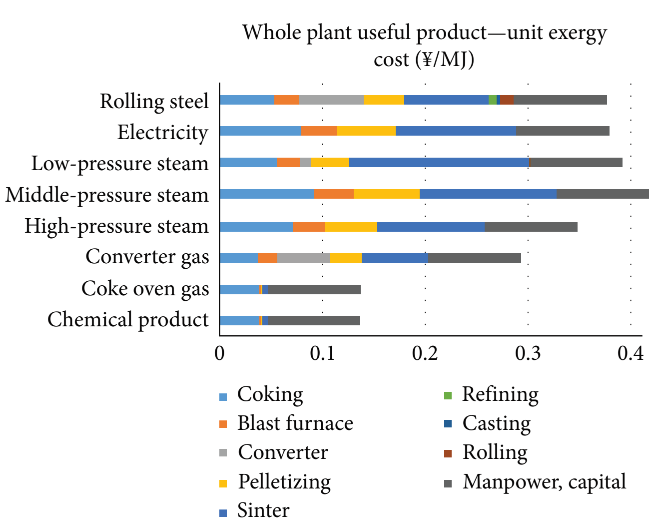

Figure 7: Whole plant product-unit exergy cost in monetary units.

differences in the choice of analysis region as compared to other models. Second, it could be attributed to the fact that other models may not fully account for manpower and capital cost, as the products are considered by-products. In such models, manpower and capital cost may only be accounted for in a single process cost balance. Conversely, the model used in this study treats all products equally based on exergy and allocates manpower and capital cost to all products. As a result, the cost of one process can have a significant impact on another process. Additionally, several assumptions were made in the model used in this study, which may deviate from the actual plant operation state. Furthermore, the model used in this study allocates waste cost to the useful product, leading to higher cost data compared to the case without waste allocation. The results of the coal gas analysis conducted in this study suggest that the cost data in other models may be underestimated, as, in reality, all external resource flows can contribute to some extent to a single process. Moreover, to

Table 8: Plant product economic cost.

Product name	COG (¥/m³)	Converter gas (¥/m³)	HPS (¥/ton)	MPS (¥/ton)	LPS (¥/ton)	Electricity (¥/kWh)	Chemical product average (¥/MJ)	Rolling steel average (¥/ton)
Cost	2.40	1.79	428	371	305	1.36	0.14	2489.50

Table 9: Cost comparison for coke oven gas and converter gas under 4 methods.

	Method 1 based on natural gas	Method 2 based on coal	Method 3 based on electricity profit	Method 4 using thermoeconomic model
Coke oven gas (¥/m³)	1.080	0.320	0.500	2.40
Converter gas (¥/m³)	0.417	0.128	0.200	1.79

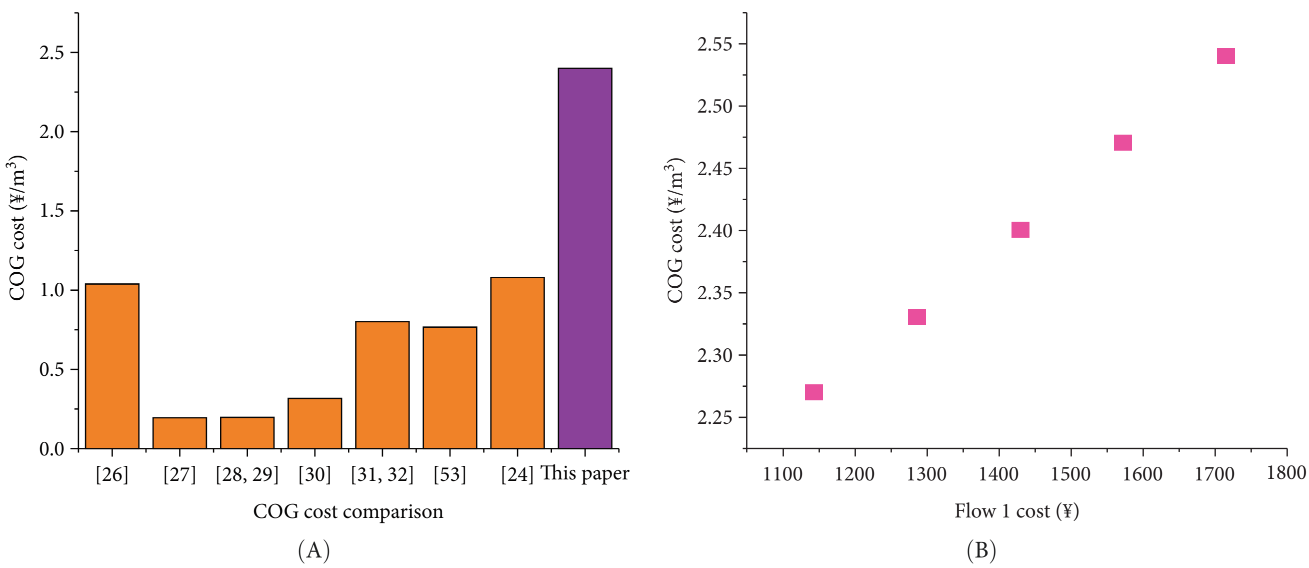

Figure 8: (A) COG cost comparison for different literature data. (B) COG cost changes when flow 1 coal cost is changing.

increase the diversity of the data, the cost of coal gas in several papers has been compared and summarized in Figure 8A. Even when compared to the cost data from [31, 32, 53–55], the cost data generated in this study are significantly higher. We further compare the COG cost when coking input cost is changing as 80%, 90%, 100%,110%, and 120% of flow 1 initial cost in order to check if the coal price change can significantly affect the COG cost. The results (Figure 8B) indicate that 80%,90%,110%, and 120% change still shows much higher cost (2.27 ¥/m^3, 2.33 ¥/m^3, 2.47 ¥/m^3, 2.54 ¥/m^3) compared with literature data. In short, the coal gas cost using heating-value-based method is severely underestimated compared with the cost data in this work. This substantial difference further underscores the need to develop a more rational approach to pricing by-product gases.

The price of steam can vary depending on the location and the steam's temperature and pressure. According to Zhang et al. [56], there are two main methods for pricing heat: cost-plus and marginal-cost pricing. The cost-plus method is commonly used in regulated heating markets, while the marginal-cost pricing method is used in deregulated markets. For instance, according to a website, the price of steam in 2019 was around 190 ¥/ton [57]. In the model system used in this study, even LPS has a cost of 305 ¥/ton, MPS is 371 ¥/ton, and HPS is 428 ¥/t. This indicates that selling steam to outside markets may not be profitable if the price is lower than the cost data. In fact, doing so would directly result in a loss of profit. Regarding the cost of electricity produced from by-product gas, [24] listed electricity at 0.15 ¥/kWh, while [27] reported a cost of 0.23–0.256 ¥/kWh. In contrast, our analysis reveals a substantially higher cost of 1.36 ¥/kWh. However, the calculation method for electricity cost produced by coal gas was not provided in [24], making it difficult to explain the reason for the differences. It is worth noting that the low input fuel cost of COG (0.196 ¥/m^3) and BFG (0.04 ¥/m^3) in [27] contributes to a much lower cost of electricity compared to other studies. This suggests that the profitability of selling by-product gas produced electricity is heavily influenced by the cost of by-product gas, which can be quite low in some plants. In short, current cost accounting methods systematically underestimate the cost of steam and electricity in ISMP. Therefore, plant management should reconsider its cost calculation methods and pricing strategies to obtain an actual market-related price for energy medium products.

7. Research Limitations, Challenges, and Future Prospects

Limitations of this study are as follows: (1) The interdependent relationships between water/steam supply and usage were not modeled in detail due to insufficient operational data. (2) Capital and labor costs were distributed evenly across production units despite actual variations in subplants. Challenges are as follows: application of exergy-based method needs detailed flow information, but most industry plants only place sensors for major purpose; therefore, real-time analysis, diagnosis, and optimization are difficult without full set of data input. Future prospects are as follows: exergy-based method can play more important role when advanced digital technology is further applied in the industry (e.g., advanced sensor technology, Internet-of-Things (IoT) technology, artificial intelligence [AI]).

8. Conclusions

In this study, a cost accounting analysis was conducted for the iron and steel plant. Initially, a flow network model was constructed, followed by a thermoeconomic analysis of the model plant. The study aims to uncover the impact of external fuel costs on product costs and estimate the costs of energy medium products. The thermoeconomic model utilized in this study presents a novel approach not only to assess the energy efficiency but also to allocate costs in a more rational manner. Our methodology takes into account the fuel costs and all production processes, representing an advancement in this field. The model system used in this study involves multiple fuel flows and product flows. We utilized a thermoeconomic model to establish the relationship between external fuel and product cost, which enabled us to obtain a comprehensive cost formation that takes into account various subprocesses and quantitatively describes the impact of one process on another. The average cost of steel products was determined to be 2489.50 ¥/ton, while the costs of COG, converter gas, HPS, MPS, LPS, and electricity were found to be 2.40 ¥/m^3, 1.79 ¥/m^3, 428 ¥/ton, 370 ¥/ton, 305 ¥/ton, and 1.36 ¥/kWh, respectively. Our findings indicate that the energy medium products cost estimated in this study is significantly higher than the cost reported in the literature. This suggests that the cost data in other models may be underestimated, highlighting the need for a more rational approach to pricing energy medium products.

Appendix A. Whole Plant Data Summary

Calculation of unknown data:

In order to calculate the data for the entire plant, certain assumptions are made to determine the values. Specifically, it is assumed that the main product of the last plant would exactly satisfy the next input need for the next plant. Based on this hypothesis, we determined that 1 ton of coke can produce 2.668 tons of molten iron and 2.726 tons of molten steel. Additionally, the entire plant produces 1.25 tons of pellet, 2.96 tons of sinter, 2.80 tons of refining molten steel, 2.74 tons of continuous casting billet, and 2.62 tons of rolling steel product. We used these ratios to calculate the exergy value for each value. The specific calculations for the ratios are as follows:

- $2.668 = 30{,}107.9/11{,}284.74$.
- $2.73 = 8814.35 \times 2.668/8625.06$.
- $1.25 = 158.31/125.8$.
- $2.96 = 1209.01/408.03$.
- $2.8 = 21{,}443.81/7665.98$.
- $2.74 = 7537.85 \times 2.9/7742.14$.
- $2.62 = 7031.38 \times 2.74/7349.74$.

Using the ratios obtained previously, the exergy of the entire plant can be calculated by multiplying each ratio with its corresponding per-ton value. The flows are represented by numerical values, and some flows are combined, as shown in Figure 1. However, the exergy values of the flows after the boiler and steam turbine are still unknown. To calculate these values, additional data are required:

- 50% of the excess coke oven gas is directed to the boiler, and the remainder is directed to coke oven gas pipeline 2. The remaining coke oven gas has a value of 2880.772 MJ, which is divided by 2 to obtain the exergy values for flow 21, flow 22, and flow 23, resulting in 1440.385 for each. Therefore, flow 22 and flow 23 are both equal to 1440.385 MJ.
- All the blast furnace gas goes to boiler, flow 20 is 6751.52 MJ; converter gas is system output; thus, flow 17 and flow 18 are 256.41 MJ; the two boilers both has exergy efficiency of 50%, and flue gas exergy loss efficiency is 1.05%; for both boilers, 10% of all the steam produced goes to high pressure steam pipeline and the rest goes to steam turbine; for both steam turbines, the exergy efficiency is 89%, and 23% of input exergy is extracted as middle pressure steam, and 17% of input steam exergy goes to low pressure steam pipeline.
- The blast furnace gas is directed to the boiler and is represented by flow 20 with a value of 6751.52 MJ. Converter gas, on the other hand, is considered as system output, hence flows 17 and 18 are valued at 256.41 MJ. The exergy efficiency of both boilers is 50%, and the flue gas exergy loss efficiency is 1.05%. For each boiler, 10% of the steam produced is directed to the high pressure steam pipeline, while the remaining steam is directed to the steam turbine. Both steam turbines have an exergy efficiency of 89%, where 23% of input exergy is extracted as middle pressure steam and 17% of input

steam exergy is directed to the low pressure steam pipeline.

The detailed calculation of these flows is (MJ unit) as follows:

- Flow 24 = 1440.385 × 20/100 = 288.077; Flue gas from boiler.
- Flow 25 = 0; Water.
- Flow 26 = 1440.385 × 0.5 × 0.1 = 72.019; High pressure steam.
- Flow 27 = 1440.385 × 0.5 × 0.9 = 648.174; High pressure steam.
- Flow 28 = 648.174 × 0.89 × 0.6 = 346.125; Work from steam turbine.
- Flow 29 = 346.125 × 0.95 = 328.818; 0.95 is generator efficiency; electricity from generator 1.
- Flow 30 = 648.174 × 0.17 = 110.189; Low pressure steam.
- Flow 31 = 648.174 × 0.23 = 149.080; Middle pressure steam.
- Flow 35 = 0; water.
- Flow 36 = 6751.52 × 20/100 = 1350.304; Flue gas from boiler.
- Flow 37 = 6751.52 × 0.5 × 0.1 = 337.576; High pressure steam.
- Flow 38 = 6751.52 × 0.5 × 0.9 = 3038.184; High pressure steam.
- Flow 39 = 3038.184 × 0.23 = 698.782; Middle pressure steam.
- Flow 32 = 337.576+72.019 = 409.595; High pressure steam.
- Flow 34 = 3038.184 × 0.6 × 0.89 = 1622.390; Work from steam turbine.
- Flow 33 = 1622.390 × 0.95 = 1541.270; 0.95 is generator efficiency; electricity from generator 2.
- Flow 41 = flow 31 + flow 40 = 665.571; Middle pressure steam.
- Flow 42 = flow 3 + flow 14 + flow 30 + flow 16 + flow 40 = 1298.453; Low pressure steam.
- Flow 43 = flow 29 + flow 13 + flow 33 = 2059; Total electricity production.

Among Table A1, only flow 85 is special as it is data from other source [51] and listed in Table A2, but all other economic data are from [50].

The element of vector Fem is calculated as follows:

- Coking: input fuel cost = 1414.85 (coal) + 12.14 (electricity) + 1.13 (steam) + 0.88 (water) = 1429 ¥.
- Blast furnace process: input fuel cost = (40.82 (ore) + 37.11 (coke scrap) + 14.79 (oxygen) + 85.52 (coal powder) + 1.74 (steam) + 5.29 (nitrogen) + 19.68 (electricity) + 17 (water)) × 2.668 = 592.16 ¥.
- Converter: input fuel cost = (189.85 (steel scrap) + 72.53 (alloy) + 0.8 (oxide iron scrap) + 15.95 (calcium oxide) + 5.24 (dolomite) + 3.06 (fluorite) + 60.46 (oxygen) + 0.81 (argon) + 61.87 (nitrogen) + 10.07 (electricity) + 3.65 (water)) × 2.726 = 1156.61 ¥.
- Pellet: input fuel cost = (727.47 (ore) + 24.33 (electricity) + 0.21(steam) + 5.01 (bentonite) + 0.46 (water)) × 1.25 = 953.24 ¥.
- Sinter: input fuel cost = (355.32 (iron ore) + 258.44 (enriched ore) + 29.45 (other ore) + 30.59 (solvent) + 22.5 (coke powder) + 21.37 (electricity) + 0.16 (steam) + 0.39 (water)) × 2.96 = 2128.08 ¥.
- Refining: input fuel cost = (24.94 (alloy) + 1.56 (lime) + 0.8 (fluorite) + 1 (steam) + 00.79 (oxygen) + 0.63 (argon) + 5.8 (nitrogen) + 11.6 (electricity) + 4.26 (slag) + 0.07 (water))× 2.797 = 143.92 ¥.
- Continuous casting: input fuel = (3.95 (oxygen) + 0.31 (argon) + 6.3 (nitrogen) + 0.34 (steam) + 11.64 (electricity) + 1.58 (water)) × 2.736 = 66 ¥.
- Rolling: input fuel cost = 0.4188 (steam)× 0.038 + (3.86 (oxygen)× 2.5532 + 0.34 (nitrogen) × 4.196 + 8.86 (hydrogen)× 0.48/31.963)× 2.6179 + 1451.303 (electricity) × 0.1417 = 235.549 ¥.

The value above is all in yuan, but the calculation for rolling process is different. For other process, there are economic data for 1 ton main product. For rolling process, the economic cost is listed in another way. Only the unit exergy cost is given; thus, the cost here is calculated by multiplying total exergy in our model system with unit exergy cost. 0.4188 MJ is steam total exergy, and 0.038 is ¥/MJ; 3.86 MJ is the oxygen exergy for 1 ton rolling steel, 2.5532 is its unit price; 0.34 is nitrogen exergy for 1 ton rolling steel, 4.196 ¥/MJ is its unit cost; 8.86 is hydrogen exergy for 1 ton rolling steel, 0.48/31.963 is unit cost data using the data in the paper; 1451.303 MJ is total electricity exergy, 0.1417 is unit cost in ¥/MJ.

Then, multiplying 891.36 (from Table A2) with 2.62, we got the cost 2333.519 ¥ for this model plant.

Table A1: Summarized initial data for each plant and its fuel and product, data from [50].

Fuel (input flows)	Exergy data (MJ)	Product (output flows)	Exergy data (MJ)
Coke oven plant (1 ton coke)			
Coke oven gas	143.51	Coke	30,107.9
Blast furnace gas	2964	Coke oven gas	7635.69
Coal	40,424.17	Chemical product	2204.38
Air	0	CDQ gas	172.52
Electricity	85.68	—	—
Low-pressure steam	29.64	—	—
Blast furnace plant (1 ton molten iron)			
Minerals	545.37	Molten iron	8814.35
Coke	11,284.74	Iron block	80.27
Coal powder	5151.95	Blast furnace gas	5716.91
Air	0	Furnace dust	361.35
Blast furnace gas	1825.75	Scrap	14.85
Coke oven gas	92.72	Hot water	12.89
Oxygen	5.8	Electricity	70.92
Nitrogen	1.26	Steam	110.7
Low-pressure steam	45.75	Flue gas	127.07
Converter plant (1 ton molten steel)			
Iron (among this iron, 8625.06 is molten iron)+steel	9608.39	Molten steel	7756.35
Fluorite+quicklime+dolomite	138.65	LDG	467.44
Coke oven gas	71.25	Slag	292.22
Blast furnace gas	24.23	Steam	74.8
Other gas	39.23	Flue gas	36.14
Electricity	71.06	Coal gas released into environment	87.43
		Iron scrap	145.32
		Other gas released	16.75
		Water discharged	0.42
Pellet plant (1 ton pellet)			
Concentrate ore+bentonite	459.14	Pellet	125.8
Blast furnace gas	53.99	Flue gas	22.72
Coke oven gas	553.95		
Steam	5.44		
Electricity	171.68		
Sinter plant (1 ton sinter)			
Ore	254.25	Sinter	408.03
Solvent	6.65	Return mine	66.17
Blast furnace gas	9.5	Recycled steam	26.13
Coke oven gas	63.57	Flue gas	115.45
Air	0		
Coke powder	1540.99		
Low-pressure steam	5.44		
Electricity	138.85		
Refining plant (1 ton molten steel)			
Molten steel	7665.98	Refined molten steel	7573.85
Alloy+lime+ fluorite+top slag +oxygen +argon+nitrogen	102.95	Refined slag	52.03
Coke oven gas	20.24	Dust and gas	4.1
Steam	26.24		
Electricity	81.83		

Table A1: Continued.

Fuel (input flows)	Exergy data (MJ)	Product (output flows)	Exergy data (MJ)
Continuous casting plant (1 ton continuous casting billet)			
Molten steel	7742.14	Continuous casting billet	7031.38
Coke oven gas	99.75	Mill scale	4.48
Oxygen+argon+nitrogen+ covering slag	4.52	Steel scrap	139.89
Steam	9.06	Water discharge and flue gas	12.78
Electricity	82.12		
Rolling plant (1 ton rolling product)			
Continuous casting billet	7349.74	Rolling product	6911.59
Coke oven gas	1128.66	Steel scrap	351.96
Blast furnace gas	192.5	Mill scale	25.47
Converter gas	388.79	Recycled steam	13.31
Steam	0.16	Flue gas+waste water	39.8
Nitrogen+oxygen+hydrogen	13.06		
Electricity	554.37		

Table A2: Cost data for manpower and capital.

Source [51]	Plate	Hot-rolled coils	Reinforced steel	Wire	Average
Manpower cost (¥/t)	135.8	81.3	68.4	78.5	588.63
Capital cost (¥/t)	52.4	54.2	37.4	43.2	302.73
Total					891.36

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

Wenwu Ding: conceptualization of this study, methodology, experiment, data analysis, writing – original draft preparation. **Sergio Usón:** methodology, data analysis, writing – original draft preparation. **Yan Long:** methodology, writing – original draft preparation.

Funding

This research was supported by the seed funding program at Xihua University (Grant Number Z241074/RX2400002015), Hubei Provincial Key Research and Development Program of China (Grant Number 2023DJC155); and Hubei Provincial Natural Science Foundation of China (Grant Number 2023AFB1062).

Acknowledgments

This research was supported by the seed funding program at Xihua University (Grant Number Z241074/RX2400002015), Hubei Provincial Key Research and Development Program of China (Grant Number 2023DJC155), and Hubei Provincial Natural Science Foundation of China (Grant Number 2023AFB1062).

References

[1] T. Hou, Y. Yuan, and H. Na, "A Comprehensive Systematic Review of CO_2 Reduction Technologies in China's Iron and Steel Industry: Advancing Towards Carbon Neutrality," *Energies* 17, no. 23 (2024): 5975.

[2] A. Song and Y. Zhou, "Advanced Cycling Ageing-Driven Circular Economy With E-Mobility-Based Energy Sharing and Lithium Battery Cascade Utilisation in a District Community," *Journal of Cleaner Production* 415 (2023): 137797.

[3] Z. Dan, A. Song, X. Yu, and Y. Zhou, "Electrification-Driven Circular Economy With Machine Learning-Based Multi-Scale and Cross-Scale Modelling Approach," *Energy* 299 (2024): 131469.

[4] Y. Zhou, "AI-Driven Digital Circular Economy With Material and Energy Sustainability for Industry 4.0," *Energy and AI* 20 (2025): 100508.

[5] A. Ziebik, M. Warzyc, and P. Gładysz, "Determination of the Optimal Structure of Repowering a Metallurgical CHP Plant Fired With Technological Fuel Gases," *Archives of Metallurgy and Materials* 59, no. i(1) (2014): 105–116.

[6] K. Matsuda, S. Tanaka, M. Endou, and T. Iiyoshi, "Energy Saving Study on a Large Steel Plant by Total Site Based Pinch Technology," *Applied Thermal Engineering* 43 (2012): 14–19.

[7] Y. Yuan, H. Na, C. Chen, et al., "Status, Challenges, and Prospects of Energy Efficiency Improvement Methods in Steel Production: A Multi-Perspective Review," *Energy* 304 (2024): 132047.

[8] H. Na, Y. Yuan, J. Sun, L. Zhang, and T. Du, "Integrative Optimization for Energy Efficiency, CO_2 Reduction, and

Economic Gains in the Iron and Steel Industry: A Holistic Approach," *Resources, Conservation and Recycling* 212 (2025): 107992.

[9] J.-C. Brunke, M. Johansson, and P. Thollander, "Empirical Investigation of Barriers and Drivers to the Adoption of Energy Conservation Measures, Energy Management Practices and Energy Services in the Swedish Iron and Steel Industry," *Journal of Cleaner Production* 84, no. 1 (2014): 509–525.

[10] K. C. Kavvadias, "Energy Price Spread as a Driving Force for Combined Generation Investments: A View on Europe," *Energy* 115 (2016): 1632–1639.

[11] M. U. Yousuf, M. A. Irshad, and M. Umair, "Identifying Barriers and Drivers for Energy Efficiency in Steel and Iron Industries of Karachi, Pakistan: Insights From Executives and Professionals," *Energy Nexus* 14 (2024): 100284.

[12] M. Xu, S. Li, Y. Wang, and Q. Liu, "Towards Green and Low-Carbon Transformation via Optimized Polygeneration System: A Case Study of the Iron and Steel Industry," *Applied Sciences* 14, no. 17 (2024): 8052.

[13] P. Ellersdorfer, C. Wang, S. Saydam, I. Canbulat, I. MacGill, and R. Daiyan, "Unlocking New Export Opportunities: An Open-Source Framework for Assessing Green Iron and Steel Supply Chains," *International Journal of Hydrogen Energy* 92 (2024): 1366–1374.

[14] K. Yamashita and L. Barreto, "Energyplexes for the 21st Century: Coal Gasification for Co-Producing Hydrogen, Electricity and Liquid Fuels," *Energy* 30, no. 13 (2005): 2453–2473.

[15] S. Sun, H. Jin, L. Gao, and W. Han, "Study on a Multifunctional Energy System Producing Coking Heat, Methanol and Electricity," *Fuel* 89, no. 7 (2010): 1353–1360.

[16] H. Jin, Y. Xu, R. Lin, and W. Han, "A Proposal for a Novel Multi-Functional Energy System for the Production of Hydrogen and Power," *International Journal of Hydrogen Energy* 33, no. 1 (2008): 9–19.

[17] L. Zhou, S. Hu, Y. Li, and Q. Zhou, "Study on Co-Feed and Co-Production System Based on Coal and Natural Gas for Producing DME and Electricity," *Chemical Engineering Journal* 136, no. 1 (2008): 31–40.

[18] H. Li, H. Hong, H. Jin, and R. Cai, "Analysis of a Feasible Polygeneration System for Power and Methanol Production Taking Natural Gas and Biomass as Materials," *Applied Energy* 87, no. 9 (2010): 2846–2853.

[19] C. He and X. Feng, "Evaluation Indicators for Energy-Chemical Systems With Multi-Feed and Multi-Product," *Energy* 43, no. 1 (2012): 344–354.

[20] W.-Q. Sun, J.-J. Cai, and J. Song, "Plant-Wide Supply-Demand Forecast and Optimization of Byproduct Gas System in Steel Plant," *Journal of Iron and Steel Research International* 20, no. 9 (2013): 1–7.

[21] J.-H. Yang, J.-J. Cai, W.-Q. Sun, and J.-Y. Liu, "Optimization and Scheduling of Byproduct Gas System in Steel Plant," *Journal of Iron and Steel Research International* 22, no. 5 (2015): 408–413.

[22] X. Zhao, H. Bai, X. Lu, Q. Shi, and J. Han, "A MILP Model concerning the Optimisation of Penalty Factors for the Short-Term Distribution of Byproduct Gases Produced in the Iron and Steel Making Process," *Applied Energy* 148 (2015): 142–158.

[23] V. B. de Oliveira Junior, J. G. C. Pena, and J. L. F. Salles, "An Improved Plant-Wide Multiperiod Optimization Model of a Byproduct Gas Supply System in the Iron and Steel-Making Process," *Applied Energy* 164 (2016): 462–474.

[24] Y. Zhu and X. He, "The Pricing Mode Discussion for Iron and Steel Enterprises By-Product Gas," *Sichuan Building Materials* 39 (2013): 244-245.

[25] J. M. Bermúdez, A. Arenillas, R. Luque, and J. A. Menéndez, "An Overview of Novel Technologies to Valorise Coke Oven Gas Surplus," *Fuel Processing Technology* 110 (2013): 150–159.

[26] H. Yao, D. Sheng, J. Chen, W. Li, A. Wan, and H. Chen, "Exergoeconomic Analysis of a Combined Cycle System Utilizing Associated Gases from Steel Production Process Based on Structural Theory of Thermoeconomics," *Applied Thermal Engineering* 51, no. 1-2 (2013): 476–489.

[27] M. Modesto, S. Nebra, and T. Morimoto, "Analysis of a Steel Mill Power System using Exergoeconomic factors," in *Proceedings of the 17th Brazilian Congress of Mechanical Engineering*no. 1, (2003)

[28] M. Modesto and S. A. Nebra, "Analysis of a Repowering Proposal to the Power Generation System of a Steel Mill Plant Through the Exergetic Cost Method," *Energy* 31, no. 15 (2006): 3261–3277.

[29] M. Modesto and S. A. Nebra, "Exergoeconomic Analysis of the Power Generation System Using Blast Furnace and Coke Oven Gas in a Brazilian Steel Mill," *Applied Thermal Engineering* 29, no. 11-12 (2009): 2127–2136.

[30] Q. Yi, J. Feng, Y. Wu, and W. Li, "3E (Energy, Environmental, and Economy) Evaluation and Assessment to an Innovative Dual-Gas Polygeneration System," *Energy* 66 (2014): 285–294.

[31] Y. Man, S. Yang, J. Zhang, and Y. Qian, "Conceptual Design of Coke-Oven Gas Assisted Coal to Olefins Process for High Energy Efficiency and Low CO_2 Emission," *Applied Energy* 133 (2014): 197–205.

[32] D. Xiang, S. Yang, Z. Mai, and Y. Qian, "Comparative Study of Coal, Natural Gas, and Coke-Oven Gas Based Methanol to Olefins Processes in China," *Computers and Chemical Engineering* 83 (2015): 176–185.

[33] X. Ye and C. Li, "A Novel Evaluation of Heat-Electricity Cost Allocation in Cogenerations Based on Entropy Change Method," *Energy Policy* 60 (2013): 290–295.

[34] X.-M. Ye, "Reduced Exergy Method for Heat-Electricity Cost Allocation in Combined Heat and Power Plants," *Entropy* 5, no. 5 (2003): 432–443.

[35] X. Feng, Y.-N. Cai, and L.-L. Qian, "A New Performance Criterion for Cogeneration System," *Energy Conversion and Management* 39, no. 15 (1998): 1607–1609.

[36] M. A. Lozano and A. Valero, "Theory of the Exergetic Cost," *Energy* 18, no. 9 (1993): 939–960.

[37] C. A. Frangopoulos, "Application of the Thermoeconomic Functional Approach to the CGAM Problem," *Energy* 19, no. 3 (1994): 323–342.

[38] G. Tsatsaronis and J. Pisa, "Exergoeconomic Evaluation and Optimization of Energy Systems—Application to the CGAM Problem," *Energy* 19, no. 3 (1994): 287–321.

[39] L. Zhong, E. Yao, H. Zou, and G. Xi, "Thermo-Economic-Environmental Analysis of an Innovative Combined Cooling and Power System Integrating Solid Oxide Fuel Cell, Supercritical CO_2 Cycle, and Ejector Refrigeration Cycle," *Sustainable Energy Technologies and Assessments* 47 (2021): 101517.

[40] J. Gao, Q. Zhang, X. Wang, D. Song, W. Liu, and W. Liu, "Exergy and Exergoeconomic Analyses With Modeling for CO_2 Allocation of Coal-Fired CHP Plants," *Energy* 152 (2018): 562–575.

[41] D. J. Kim, "A New Thermoeconomic Methodology for Energy Systems," *Energy* 35, no. 1 (2010): 410–422.

[42] A. M. El-Nashar, "Cost Allocation in a Cogeneration Plant for the Production of Power and Desalted Water— Comparison of the Exergy Cost Accounting Method With the WEA Method," *Desalination* 122, no. 1 (1999): 15–34.

[43] O. Hamed, H. Alwashmi, and H. Alotaibi, "Thermoeconomic Analysis of a Power/Water Cogeneration Plant," *Energy* 31, no. 14 (2006): 2699–2709.

[44] M. A. K. Al-Sofi and M. M. Srouji, "Fuel Allocation in Dual-Purpose Plants," *Desalination* 100, no. 1–3 (1995): 65–70.

[45] C.-E. Grip, M. Larsson, S. Harvey, and L. Nilsson, "Process Integration. Tests and Application of Different Tools on an Integrated Steelmaking Site," *Applied Thermal Engineering* 53, no. 2 (2013): 366–372.

[46] Y. Yang, T. Du, Y. Li, et al., "Techno-Economic Assessment and Exergy Analysis of Iron and Steel Plant Coupled MEA-CO_2 Capture Process," *Journal of Cleaner Production* 416 (2023): 137976.

[47] C. Torres, "Symbolic thermoeconomic analysis of energy systems," in *Exergy, energy system analysis and optimization, from encyclopedia of life support systems (EOLSS)*, ed. C. A. Frangopoulos, (EOLSS Publishers, Oxford, Chapter 13, 2006).

[48] C. Torres, A. Valero, V. Rangel, and A. Zaleta, "On the Cost Formation Process of the Residues," *Energy* 33, no. 2 (2008): 144–152.

[49] S. Usón, A. Valero, and A. Agudelo, "Thermoeconomics and Industrial Symbiosis. Effect of By-Product Integration in Cost Assessment," *Energy* 45, no. 1 (2012): 43–51.

[50] D. Lang, *Exergy Analysis and Thermoeconomic Analysis of Energy-saving Technology in Iron and Steel Enterprises*, (Master Thesis, Northeastern University, 2011).

[51] China Steel Development and Research Institute, "Analysis and Comparison of Cost and Competition Power for Chinese and Foreign Iron and Steel Industry in 2011," *Metallurgical Management* 6 (2012): 4–12.

[52] Y. Tian, *Study on Reasonable Utilization and Optimizing Distribution of Steam in Iron and Steel Company (In Chinese)*, (Master Thesis, Northeastern University, 2011).

[53] Y. Hao, Y. Huang, M. Gong, W. Li, J. Feng, and Q. Yi, "A Polygeneration From a Dual-Gas Partial Catalytic Oxidation Coupling With an Oxygen-Permeable Membrane Reactor," *Energy Conversion and Management* 106 (2015): 466–478.

[54] S. Kim, M. Kim, Y. T. Kim, G. Kwak, and J. Kim, "Techno-Economic Evaluation of the Integrated Polygeneration System of Methanol, Power and Heat Production From Coke Oven Gas," *Energy Conversion and Management* 182 (2019): 240–250.

[55] J.-K. Lee, S. Shin, G.-J. Kwak, M.-K. Lee, I.-B. Lee, and Y.-S. Yoon, "Techno-Economic Evaluation of Polygeneration System for Olefins and Power by Using Steel-Mill Off-Gases," *Energy Conversion and Management* 224 (2020): 113316.

[56] J. Zhang, B. Ge, and H. Xu, "An Equivalent Marginal Cost-Pricing Model for the District Heating Market," *Energy Policy* 63 (2013): 1224–1232.

[57] China Clean Heating Platform, "Newest industry steam price from Jiangsu, Zhejiang, Shandong provinces," Technical Report (2019).