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Material and energy flows of the iron and steel industry: Status quo, challenges and perspectives

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HIGHLIGHTS

- A review of material and energy flows in the iron and steel industry is provided.
- Material scheduling and energy saving technologies for steelworks are reviewed.
- Forecasting and optimization models of material and energy flows are introduced.
- Challenges of current studies on material and energy flows are identified.
- Future directions of material flow and energy flow research are discussed.

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ABSTRACT

Integrated analysis and optimization of material and energy flows in the iron and steel industry have drawn considerable interest from steelmakers, energy engineers, policymakers, financial firms, and academic researchers. Numerous publications in this area have identified their great potential to bring significant benefits and innovation. Although much technical work has been done to analyze and optimize material and energy flows, there is a lack of overview of material and energy flows of the iron and steel industry. To fill this gap, this work first provides an overview of different steel production routes. Next, the modelling, scheduling and interrelation regarding material and energy flows in the iron and steel industry are presented by thoroughly reviewing the existing literature. This study selects eighty publications on the material and energy flows of steelworks, from which a map of the potential of integrating material and energy flows for iron and steel sites is constructed. The paper discusses the challenges to be overcome and the future directions of material and energy flow research in the iron and steel industry, including the fundamental understandings of flow mechanisms, the dynamic material and energy flow scheduling and optimization, the synergy between material and energy flows, flexible production processes and flexible energy systems, smart steel manufacturing and smart energy systems, and revolutionary steelmaking routes and technologies.

1. Introduction

As the second largest energy user in the global industrial sectors [1], the iron and steel industry is highly dependent on fossil fuels [2] and releases massive amounts of environmentally harmful substances [3]. With rapid urbanization and industrialization, the demand for steel has increased over the last several decades [4]. Crude steel production reached 1870 Mt globally for the year of 2019, with energy intensity of 20 GJ per tonne of crude steel [5], fresh water intensity of 3.3 m^3 per tonne of crude steel [6], and a CO_2 emission intensity of 1.9 t per tonne of crude steel [7]. Previous studies have concluded that the increasing output of crude steel is the most important factor leading to the remarkable increase in the total energy consumption and environmental emissions of the iron and steel industry. By contrast, decreasing the energy intensity (i.e. specific energy consumption [8]) is the most important factor that reduces gross energy consumption and emissions [9,10]. Energy efficiency improvement or energy conservation are the most controllable factors that influence the energy consumption and

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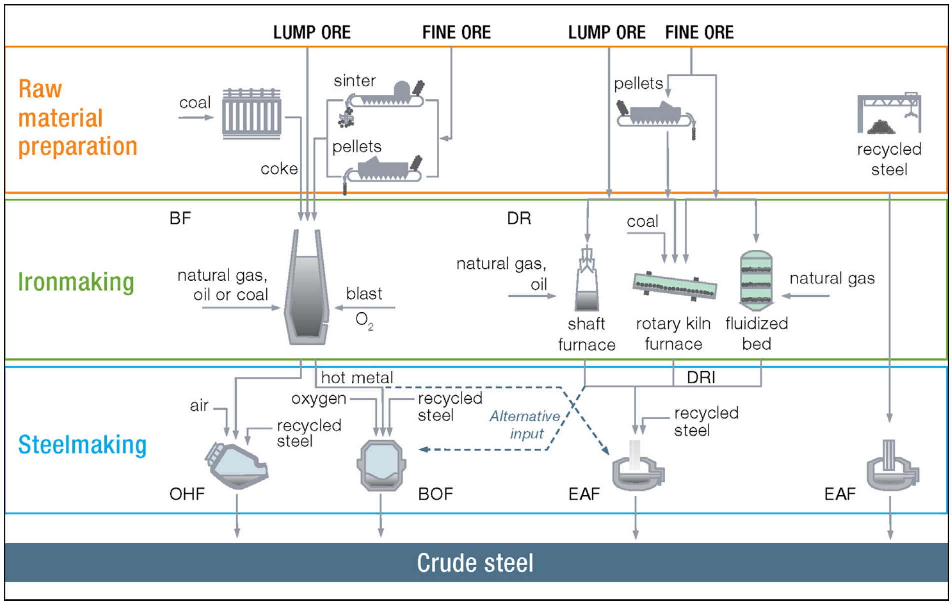

Fig. 1. Iron and steel production routes [14].

emissions of the iron and steel industry, and climate change and rising energy prices further increase their importance [11]. However, the opportunity to achieve energy savings becomes narrower and narrower after decades of hard work by the iron and steel community [12].

With the rapid development of global informatization, modern steelworks are equipped with the enterprise resource planning (ERP) systems and manufacturing execution systems (MESs), meeting the basic hardware requirements for fast information transmission of material flow and networked energy flow management [13]. The current computer integrated manufacturing systems (CIMSs) have great field data acquisition and monitoring capability, which enables the integration of material and energy flows. However, the efficient, optimal, and smart scheduling and the synergistic interaction of material flow and energy flow have not been fully implemented yet. Thus, it is essential to figure out the operating rules of material and energy flows and achieve the dynamic optimization and synergistic operation of them.

There have been many studies conducted on integrating material and energy flows in the iron and steel industry in recent years. In order to identify challenges and solutions to reduce energy intensity and cost of the iron and steel industry, it is necessary to conduct a systematic literature review of material and energy flows in steelworks. The literature review in this paper aims to compile the relevant contributions from previous publications. The review covers journal articles and conference papers from the publication databases of ScienceDirect, Springer, Taylor & Francis, CNKI, Wiley Online and IEEE Xplore, as well as white papers and industrial reports. This paper attempts to provide a timely and comprehensive review of the material and energy flows of the iron and steel industry with no limitation on the publication years. More specifically, the contributions of this review paper are as follows:

First, an overview of the steel production routes is provided by summarizing different route architectures. In addition, the material and energy flows and the dynamic operation of the steel production process are briefly introduced. These contents are presented in Section 2 to provide readers with an in-depth understanding of steel production processes.

Next, the status quo of the practice and research on the material and energy flows of the iron and steel industry is presented. Many journal articles, conference papers, white papers and industrial reports have been reviewed here. The selected publications are divided into three categories, namely, (1) material flow and material flow scheduling, (2) energy flow and the energy flow network, and (3) the interrelation between material and energy flows. For each of these categories, we discuss the principles, technologies, mathematical models, as well as the potential problems that must be overcome for future development. The present review differs substantially from the existing ones, classifying the initiatives according to their specific models/algorithms and technical characteristics. To our knowledge, this paper is the first systematic review of material and energy flows in the iron and steel sector, based on the state-of-the-art studies that have been conducted so far in this area.

Finally, an in-depth discussion of the challenges of material and energy flows is conducted. Insights about where integrated material and energy flow research is heading are provided, with the energy-related issues for the iron and steel industry discussed.

2. Steel production routes

2.1. Classification of steel production routes

Steel is produced via the following two main routes, which are characterized by the type of raw material and energy consumed.

(a) The blast furnace–basic oxygen furnace (BF–BOF) route. About 75% of steel in the world is produced by using the BF–BOF route [14], in which iron ores are reduced to iron, also called pig iron or hot metal, in the BFs. Then, the iron is converted to steel in the BOFs. For the BF–BOF route as shown in the left-hand side of Fig. 1, the material inputs are predominantly iron ores and the energy inputs are coal and electricity [15]. The steel is produced with several processing steps, including coking, sintering, pelletizing, ironmaking, primary and secondary steelmaking, casting, and hot rolling [16]. These processes are generally followed by various fabrication processes, including cold rolling, forming, forging, joining, machining, coating, and heat treatment [17]. Finally, the steel is delivered as coils, plates, sections, or bars.

Another steelmaking technology using hot metal from BFs as the main material is open hearth furnaces (OHFs). The OHF process is highly energy intensive. Owing to its environmental and economic disadvantages, the OHF process makes up only about 0.4% of global steel production and is still in decline. Therefore, the OHF process is not discussed in this paper.

(b) The electric arc furnace (EAF) route. About 25% of steel in the world is produced via the EAF route [18]. The EAF route produces steel using recycled steel scrap as the major raw material and electricity as the major form of energy. Additives, such as alloys, are used to adjust to the desired chemical composition. Depending on the availability of recycled steel and the plant configuration [19], other sources of metallic iron, such as direct reduced iron (DRI) or hot metal, can also be used in the EAF route [20], as shown in the right-hand side of Fig. 1. Downstream processes, such as casting, reheating and rolling, are similar to those in the BF–BOF route.

Variations and combinations of production routes also exist. Casting iron is sometimes produced in the BFs without being sent to the BOFs [21]. In addition, most steel products will remain in service for decades before they are recycled, resulting in the fact that current recycled steel scrap is not enough to meet the growing demand for steel production if the EAF route is used alone. Therefore, a combination of the BF–BOF and EAF routes is usually used [22]. For example, hot metal from BFs can also serve as an input of EAFs.

The iron and steel industry is facing challenges because it would like to achieve multiple objectives at the same time. The objectives include maintaining high product quality, boosting productivity, reducing business costs, reducing energy consumption, and mitigating environmental emissions. To recognize and overcome these challenges, the integration of material and energy flows should be put forward as a crucial concern [18,23], rather than treating the material flow and energy flow separately.

2.2. Material and energy flows in steelworks

In this paper, the term *flow* refers to any dynamic variation of material and energy with time. As shown in Fig. 2, material flows present the dynamic movement and transformation of iron-bearing materials [23], including iron ores, steel scrap, hot metal, liquid steel, cast slabs, finished steel, etc. Energy flows include coke, coal, blast furnace gas (BFG), coke oven gas (COG), Linz–Donawitz converter gas (LDG) or BOF gas, power, water, steam, waste heat, compressed air, etc. [18,24]. In the iron and steel production processes, energy flows serve as drivers, reaction agents, and thermal media to process material flows efficiently, economically, and sustainably.

2.3. Dynamic operation of the steel production process

Complicated iron and steel production processes can be simplified to processes of the input-output of material flows, the input-output of energy flows, and the interaction of material and energy flows [23]. The essence of the iron and steel production processes has been revealed as dynamically ordered displacement and conversion of material and energy flows under designed process networks. These designed networks involve the material flow network and energy flow network in the steel production process, respectively [26].

The concept of an energy flow network in the steel production process has been widely accepted and actively promoted. An energy system is a complex system which contains the conversion and transfer of various energy forms [27]. To achieve the networked management of different forms of energy, an IDDD + N principle (i.e., Integration of the processes, Differentiation of the demand, Diversification of the supply, Decentralization of the grid, and Network of multi-energy flows) was proposed for achieving systemic energy conservation and a synergistic energy system [28].

Two major international conferences ('The 2nd European Steel Technology and Application Days (ESTAD)' held in 2015 in Düsseldorf, Germany [29] and 'The 148th TMS Annual Meeting' held in 2019 in Texas, USA [30]) indicated that the dynamic optimization and synergistic operation of material and energy flows would give birth to a new round of energy-saving technology innovations in the iron and steel industry.

3. The State of the art of material and energy flows

The research of material and energy flows in iron and steel production processes is still at an early stage and is currently gaining momentum. Publications on this topic generally fall into three categories, namely, (i) material flow and material flow scheduling, (ii) energy flow and energy flow network, and (iii) the interrelation between material and energy flows.

3.1. Material flow and material flow scheduling

Material flow influences the energy intensity of the iron and steel production processes. To reduce the energy intensity, much work has been done from the perspective of material flow. A widely used model for analyzing the influencing factors of energy intensity per tonne of crude steel is the *e*–*p* analysis model [18,31]. It mainly focuses on material flow and is expressed as follows:

$$E = \sum_{i=1}^{I} e_i p_i, \quad i \in \{1, 2, \cdots, I\}, \tag{1}$$

where *i* is the plant index, and plants include coking, sintering, pelletizing, ironmaking, steelmaking, hot rolling, and on-site power plants,

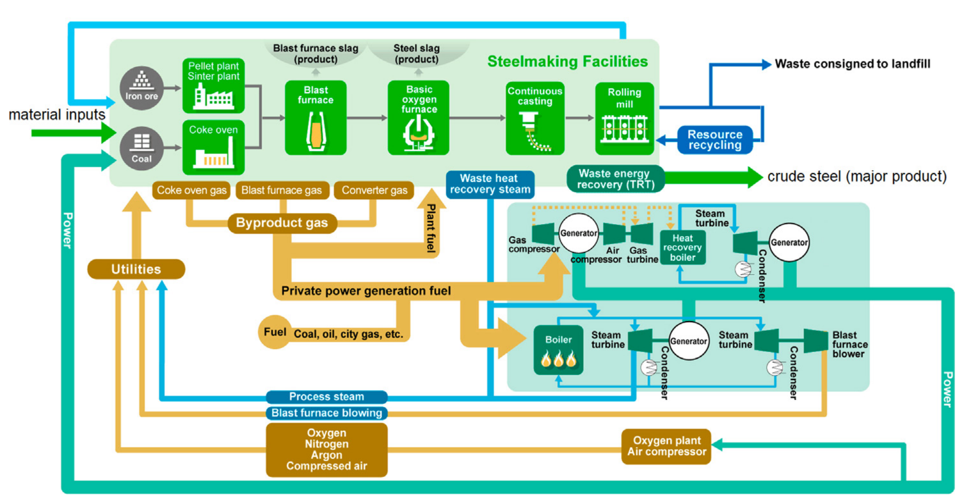

Fig. 2. Material and energy flows in BF–BOF steelworks [25].

etc.; I is the total number of plants; E is the comprehensive energy consumption per tonne of crude steel, also called the energy intensity of the whole site, [tonnes of coal equivalent (tce)/t]; e_i is the plant energy consumption per tonne of major product produced in plant i, also called the energy intensity of plant i, [tce/unit of product]; and p_i is the product ratio of plant i, [unit of product/t], which is expressed as follows:

$$p_i = P_i/P, \tag{2}$$

where P is the output of crude steel of the whole site, and P_i is the output of the major product of plant i.

It can be seen from Eq. (1) that the factors influencing the energy intensity of the whole site include (i) plant energy intensity, e, (ii) product ratio, p, and (iii) the number of plants, I. Previous studies have mainly concentrated on the importance of e and p, but less attention has been paid to I. These studies were conducted at plant and facility levels, including thick layer iron ore sintering, beneficiated burden material policies for BFs, the rolling of ingots with liquid cores, and the production of energy-efficient products [32]. Afterwards, the iron and steel community realized the importance of I and eliminated a number of less-efficient technologies and facilities, such as die casting, blooming, cupolas, and open hearth furnaces [18], with several advanced technologies developed as well, including "rolling in one heat" and "one ladle from BF to BOF" [33].

At the very beginning, most of the main processes of the iron and steel sites operated in a batch type configuration, hindering productivity improvements and the integrated coordination of multiple processes. Thus, many significant improvements have been made for the optimized scheduling of material flow, with the goal of transitioning towards maximal continuity and compactness. Table 1 summarizes the literature on material flow optimization.

Based on literature survey, the German iron and steel industry started very early to optimize and schedule material flow. The variety of steel grades produced in BOF plants require different treatment steps and intensities, causing a 1:4 range in processing time for refining and casting [49]. For the control of the complex processing steps, Hüttenwerke Krupp Mannesmann GmbH (HKM), in Huckingen, developed a computer scheduling system, namely, the Dispo-system [34], which is used to control the complex processes and improve the temperature adjustment in the steelmaking plant. The system is the solution to visualize actual and future production conditions [35]. For further improvement, a satellite system was developed to control the complex logistics in the BOF plant, which shows an increase in production output of 10%–15% when compared with conventional expert systems [36].

The Austrian steel industry has carried out lots of work to develop expert material flow scheduling systems. The Voest Alpine Scheduling Expert system, developed by voestalpine Stahl GmbH, showed that the scheduling problem cannot be solved by using programming techniques or expert systems alone. A combined approach of expert system, database management, and conventional programming techniques was proven to be an adequate solution [38]. Voestalpine has also designed a procedure that assists the operator in the generation of hot-charging and rolling schedules. The objectives include the significant increase in the slab temperature in reheating furnaces, at the same time maintaining the due date performance targets. It consists of a number of local detailed schedulers and aims to generate near optimal schedules that gain more business benefits in the context of caster and hot mill synchronization, process restrictions, and production constraints [39].

The iron and steel industry in other countries, such as Canada [41,42], the UK [43,50], and Japan [44,51], also have worked hard on material flow scheduling. The most representative system is the system developed by Paul et al. for monitoring large-scale distributed processes and modifying control plans in real time in response to deviations from the planned production schedule [45].

As the largest steel producer globally, China began to optimize material flow in the 1980s. The promotion of continuous casting has enabled the whole steelmaking process to increase in scale and become continuous and automatic, significantly reducing the energy consumption of steelmaking plants. In the 21st century, blowout studies on material flow scheduling have been made by Chinese researchers [46,47,48]. A representative achievement is the multi-functional material flow scheduling proposed by Yin [33]. From the view of engineering science, the steel manufacturing process features the decision and optimization of state change, property control, and the process scheduling of material flow in the production network.

It can be concluded that the early work on material flow scheduling has mainly focused on BOF plants, where the steelmaking–continuous casting zone is usually regarded as a cornerstone and bottleneck in a modern integrated steel company [48]. In recent years, material flow scheduling has been extended to the upstream hot metal transport [40] and downstream hot rolling mill [43]. With the development of material flow scheduling, modern iron and steel production processes have become more and more compact and the total metallurgy time has become shorter and shorter. However, all the above-mentioned studies were made with the assumption of a sufficient energy flow supply. It is worth noting that the scheduling/rescheduling of material flow will cause a variation in the instantaneous generation and consumption of energy flows [18]. Material flow scheduling with varying energy flow constraints is still a research gap at present.

3.2. Energy flow and energy flow network

Another model for analyzing the influencing factors of energy intensity per tonne of crude steel is the c–g analysis model [52]. It decomposes the energy intensity on the basis of energy flow and is expressed as follows:

$$E = \sum_{k=1}^{K} c_k g_k, \quad k \in \{1, 2, \cdots, K\}, \tag{3}$$

where k is the energy flow (energy carrier) index, and the energy flows include coal, coke, blast furnace gas, coke oven gas, Linz–Donawitz converter gas, natural gas, electricity, water, steam, oxygen, hot blast, compressed air, etc.; K is the total number of energy flows; c_k is the unit conversion factor of energy flow k, called the standard coal coefficient of energy flow [kgce/unit of energy carrier]; and g_k is the amount of energy flow k consumed in the site, measured in GJ for steam, m^3 for fuel gases and other gaseous carriers, kWh for electricity, and t for water and solid fuels.

It can be seen from Eq. (3) that the factors influencing the energy intensity of the whole site include (i) standard coal coefficient of energy flow, c, (ii) consumption of the energy flow, g, and (iii) the number of energy flows, K. Besides the material flow optimization described in Section 3.1, more detailed work has been conducted on the optimization of c and g. A series of key generic technologies have been developed, such as high temperature air combustion (HTAC) [53], BFG dry dedusting and recovery [54], LDG dry dedusting and recovery [55], BFG top-pressure recovery turbine (TRT) [56], coke dry quenching (CDQ) [57], pulverized coal injection (PCI) [58], process excess heat recovery [59], organic Rankine cycle (ORC) power generation [60], enhanced heat transfer [61], energy storage [62], and replacement with energy-efficient machines [63]. The adoption of the above-mentioned energy-efficient measures can significantly reduce energy usage in the iron and steel industry [64]. Table 2 summarizes the various energy-saving technologies for the iron and steel industry.

Besides the individual energy-efficient technologies, the rapid development of energy flow network optimization has enhanced the energy efficiency of the whole industry significantly in recent years, with attention paid to mainly two aspects, namely, physical models of the energy flow network and mathematical models for energy flow forecasting and scheduling.

Table 1
Summary of the studies on material flow scheduling.

Country	Problem description	Methods	Developed tools / models	Application	Benefits	Refs.
Germany	Optimization of the material flow from hot metal desulfurization to the end of the cast.	Combination of computer-based calculations and manual operation.	Dispo-system.	A BOF plant of HKM.	It shortened the processing time and waiting time caused by crane transport activities.	[34,35]
Germany	Optimization of the slab finishing department.	A satellite system was developed to control the complex logistics.	Satellite-integrated control system.	A BOF plant of HKM.	An increase in productivity of 20 heats per shift (approximately 10%–15%).	[36]
Germany	Optimization of EAF operation to reach the lowest production cost.	Extension of an existing European electricity market model.	Simulation.	Several EAF plants of German steelworks.	Approximately 50% of steel mills in Germany have pre-qualified their EAFs as positive capacity.	[37]
Austria	Optimal scheduling for a BOF plant.	Combined approach of expert system technology, conventional programming, and database management.	Voest Alpine Scheduling Expert (VASE) system.	A BOF plant of VASL.	The VASE's schedule was at least as good as that produced by the most experienced human experts.	[38]
Austria	The logistics of hot charging and its challenging scheduling between casters and the hot strip mill.	A scheduling solution where different scheduling components collaborated.	SteelPlanner.	Hot rolling plant of VASL.	It can be used for caster scheduling, hot strip mill scheduling, material flow synchronization and hot charge optimization.	[39]
Austria	Torpedo scheduling problem that deals with the optimization of the transport of hot metal from BFs to BOFs.	A new approach utilizing a multi-stage simulated annealing process.	Algorithm to solve the problem.	The BF–BOF production route of an Austrian steelworks.	It is a valid and competitive method to solve the problem.	[40]
Canada	Steel production scheduling problem	An algorithm based on an implicit enumeration procedure.	An enumeration-based algorithm.	A BOF plant and a hot rolling plant of a Canadian steelworks	Large potential savings from the optimal schedules over the manually generated schedules.	[41]
Canada	Optimal scheduling and sequencing of production within a hot rolling plant.	Width-grouping algorithm and thickness group clustering.	A set of models and a solution algorithm.	ArcelorMittal Dofasco's hot strip mill in Hamilton, Ontario, Canada.	Reoccurring monetary benefits of greater than 1.2 million CAD/year.	[42]
UK	Integrated optimization and dynamic scheduling of the continuous caster and the hot strip mill.	A novel distributed intelligent multi-agent approach.	A software prototype.	Not specified.	Multi-agent systems are a well-suited approach for the problem.	[43]
Japan	Scheduling of steelmaking processes.	A cooperative scheduling method.	Scheplan.	Nippon Kokan Co., Ltd.	The schedule can be obtained efficiently in a reasonable time.	[44]
Japan	Scheduling of continuous–caster steel mills.	Reactive scheduling and control method.	A computer system.	Not specified.	The system was extended as a commercial product for online monitoring and reactive scheduling.	[45]
China	Scheduling of steelmaking–continuous casting production.	A non-linear model based on actual production situations.	Mathematic models.	Example demonstration.	The model was used to optimize production continuity and product delivery while eliminating machine conflicts.	[46]
China	Production order scheduling.	Deterministic mixed integer programming and Lagrangian relaxation method.	A production order scheduling simulation system.	Baosteel.	The proposed method was stable and could find good solutions within a reasonable time.	[47]
China	Energy-oriented flow shop scheduling with limited buffers.	Energy-oriented multi-objective optimization (EOMO) algorithm.	Computational experiments.	Not specified.	The proposed algorithm presents high capabilities in handling multi-objective scheduling problems in hybrid flow shop scheduling.	[48]

Abbreviations: HKM—Hüttenwerke Krupp Mannesmann GmbH; VASL—voestalpine Stahl GmbH, Linz.

Table 2
Summary of energy-saving technologies for the iron and steel industry.

Energy-saving technologies	Energy flow types	Applications	Energy-saving potential	Refs.
High temperature air combustion (HTAC)	BFG, COG, and LDG	Reheating furnace and hot blast stove	An increase of 20%–30% in thermal efficiency.	[53]
Top-pressure recovery turbine (TRT)	BFG	BFG pressure reduction	Approximately 30 kWh/t of electricity generation.	[56]
BFG dry deducting and recovery	BFG	Raw BFG dedusting	An increase of 30% in TRT power generation and an increase of 5%–8% in the lower heating value (LHV).	[54]
LDG dry dedusting and recovery	LDG	Raw LDG dedusting	An increase of 45 t/h in steam generation and an increase of about 5% in LHV.	[55]
Coke dry quenching (CDQ)	Coke	Coke quenching	95–105 kWh/t(coke) of electricity generation.	[57]
Pulverized coal injection (PCI)	Coal	BFs	A reduction of 10 kg/t(HM) in coke ratio when PCI increases by 15 kg/t(HM).	[58]
Process excess heat recovery	Sensible heat of sinter and slab	Sinter strand; slab conveyor	A reduction of 15–25 kgce/t(sinter) and an increase of 53.7% in electricity generation.	[59]
Organic Rankine cycle (ORC)	Waste heat, hot water, and steam flow	Distributed low-temperature sources	The exergy efficiency of 30%–55%.	[60,65]
Enhanced heat transfer	Waste heat and gas flow	Heat exchangers	An increase of 6%–24% in the convective heat transfer coefficient.	[61,66]
Energy storage	Gas, steam, power, and waste heat	Where energy flow needs storage	The energy efficiency is 65%–85%.	[62,67]
Energy-efficient machines	Power flow and water flow	Fan and pump	A reduction of nearly half in power consumption.	[63,68]

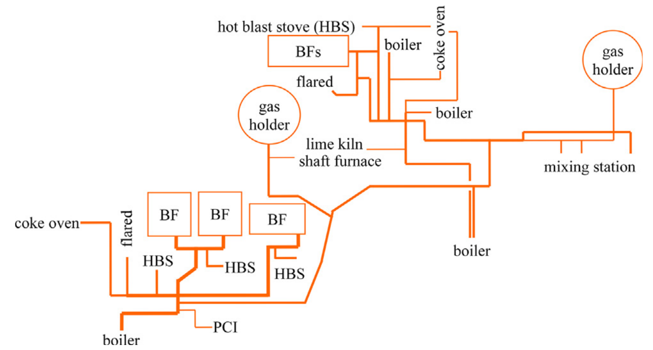

Fig. 3. The physical model of a BFG sub-network.

3.2.1. *Physical models*

Energy flow is regarded as the amount of energy flowing from one piece of equipment to another [69]. The structure of an energy flow network is thus the combination of paths through which energy carriers, such as electricity and heat, flow in the iron and steel production processes.

(a) Gas network

Many studies have been conducted with an emphasis on one sub-network or subsystem of the whole energy flow network in steelworks. The gas network is the one studied most frequently, because of its important role in the whole network [70]. Purchased gas is mainly natural gas and byproduct gases of steel production processes include COG, BFG, and LDG. Some steelworks mix BFG with COG or mix the three gases to create mixed gas (MG). For a gas flow sub-network, originally the physical model was usually set up based on the geographical and geometric characteristics of the gas pipelines, as shown in Fig. 3. Afterwards, more and more researchers concentrated on the interchangeability and coordinated use of multiple gas [71], neglecting the spatial locations, as shown in Fig. 4 [72].

(b) Steam network

Likewise, the physical model of the steam network can also be set up with and without considering the spatial locations (as shown in Fig. 5 [73]). The physical model shown in Fig. 5 visualizes the generation and utilization of steam of different grades in the whole steelmaking site.

(c) Multi-energy network

Only a few publications were found on the establishment of multiple energy flows in the whole site [18,74]. According to the energy flow input and output characteristics, the energy flow network can be classified into five systems, namely, energy conversion system, energy use system, waste heat recovery system, energy buffer system, and energy

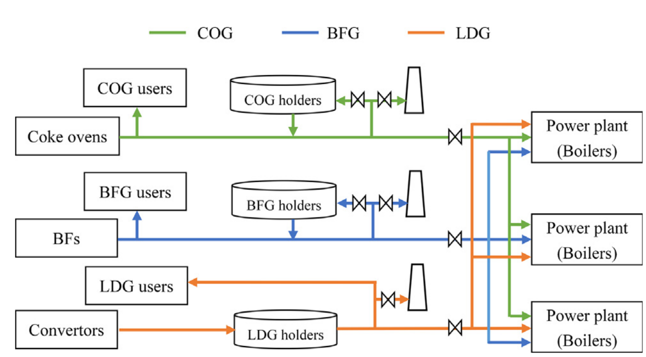

Fig. 4. The physical model of a gas network [72].

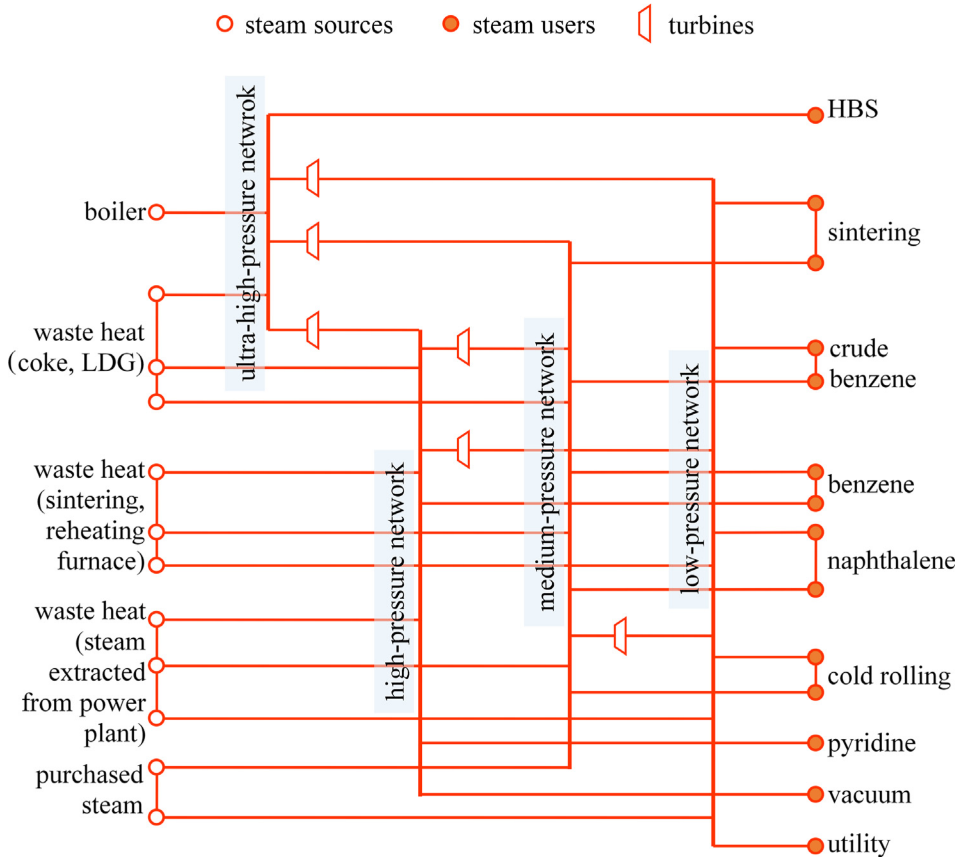

Fig. 5. The physical model of a steam network without considering spatial locations [73].

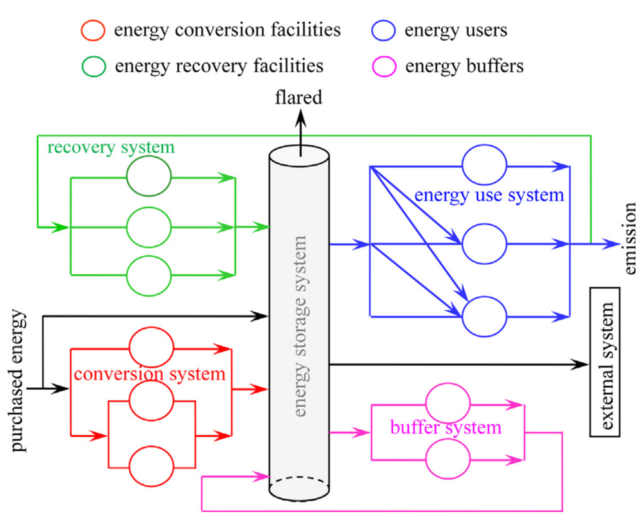

Fig. 6. The energy flow network model of the whole steelmaking site [74].

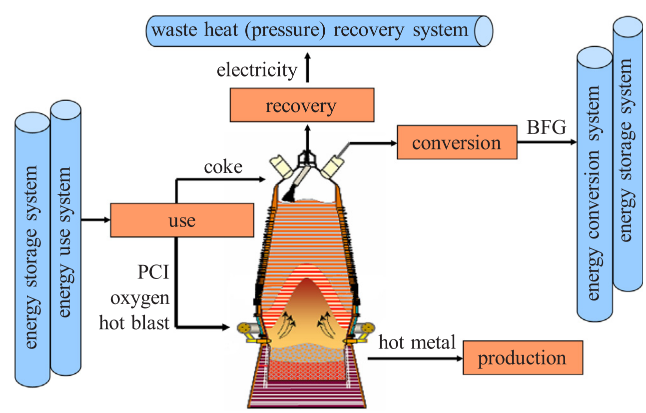

Fig. 7. BF as a prosumer in the energy flow network.

storage system. A physical model of the whole energy flow network can be built as shown in Fig. 6.

Actually, many facilities in iron and steel sites produce and consume energy simultaneously. For instance, coke ovens consume coal and produce coke and COG. BOFs consume electricity and oxygen and produce LDG. Boilers consume works arising gas and produce steam and even cooling [75]. These facilities, which both produce and consume energy carriers, are called prosumers [76]. As shown in Fig. 7, the BF serves as a prosumer in the energy flow network. When it performs its task of hot metal production, it consumes coke, PCI and hot blast from the energy use system, and oxygen from the energy storage system. Simultaneously, it converts coke and PCI into BFG through the energy conversion system, which will be sent to energy storage system. In addition, it converts the top pressure to electricity via the waste energy (pressure) system. Thus, energy flow sub-networks can be integrated into the whole energy flow network through the prosumer nodes in the network. As shown in Fig. 8, the gas network, the steam network, and the electricity network can be integrated into a larger network.

3.2.2. Mathematical models

Mathematical modelling is an important basis for the optimization of the energy flows and energy flow networks. However, widely-used energy system models such as the MARKAL model [77] and LEAP model [78] are mainly focused on national- or industrial-sector-levels, while less attention has been paid to site-wide energy systems [79]. For the iron and steel production processes, although mature energy system

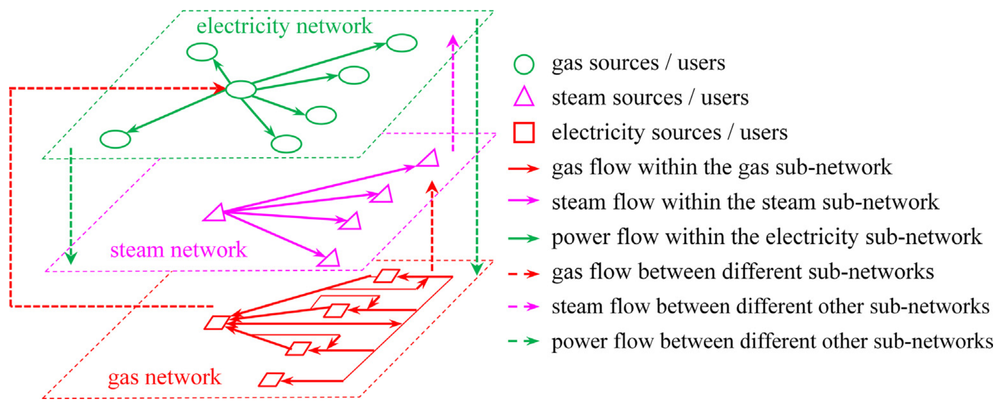

Fig. 8. Integration of energy flow sub-networks.

models and software are less used in practice, many steelworks have integrated some energy flow optimization models to some degree. Ispat Inland Steel and voestalpine Stahl are two of the earliest steelworks who built energy flow models [80]. Afterward, more researchers conducted many investigations on the mathematical models [81].

Aiming at forecasting and optimizing energy flows, at first, various static supply and demand models of energy flows have been established to report energy flow balances. Afterwards, dynamic forecasting and scheduling models were built mainly in an attempt to guide production.

For forecasting the supply and demand of energy flows, many forecast methods and models have been developed, which can be classified into two categories, namely, time series forecasting and causal relationship forecasting. For time series forecasting, statistical analysis on historical data are carried out to figure out the variation of the unknown quantity with time. The time series models applied in energy flow forecasting include the Box–Jenkins model [82], moving average models [83], and Markov methods [84]. For causal relationship forecasting methods, the forecasting models are built based on the deterministic function or nondeterministic correlational relativity between the known and unknown quantities. The causal models used in energy flow forecasting include regression analysis models [85], artificial neural network (ANN) models [86], genetic algorithm (GA) models [87], echo state networks [88], and grey models [89]. A more detailed summary of the literature on the energy flow forecasting is presented in Table 3. It can be seen that most work focuses on gas flow.

Although many energy flow forecasting methods have been developed with a high accuracy, fewer models have been established on the basis of material flow. Actually, the variation in material flow influences the energy flow, both directly and decisively. Therefore, a material flow-based energy flow forecasting method has the potential of reducing the model complexity and computational burden, which thus should be further developed in the future. In addition, almost all the previous studies have focused on the energy flow quantity, but the forecast of the energy quality, such as the LHV for gas flow and the pressure and temperature for steam flow, is still lacking.

Compared with material flow optimization, the research on dynamic energy flow optimization is still at an early stage. The main models used in energy flow scheduling include linear programming models [94], mixed integer linear programming (MILP) models [95], dynamic programming models [96], and heuristic models [97]. The energy scheduling unit model is often used to solve plant-wide energy flow scheduling problems. In the model, the energy system is divided into four groups, namely, rigid energy consuming units, flexible energy consuming units, energy conversion units, and energy buffer units, which are basically consistent with the physical model structure proposed in Fig. 6. In the mathematical programming models, minimized cost is usually selected as the objective. Many researchers have studied the optimization and scheduling of surplus energy flow, especially surplus gas flow [98]. In addition, the scheduling of steam, oxygen, and waste heat flows in the iron and steel production processes have also

Table 3
Summary of energy flow forecasting methods.

Energy flow types	Forecasting methods	Description	Refs.
BFG	Echo state neural network (ESN)	● The error of BFG generation is 1.6%–6.9%. ● The error of BFG demand in HBSs is 5.0%–12.1%.	[88]
BFG	Hybrid event-, mechanism- and data-driven prediction	● The hybrid event-, mechanism- and data-driven model exhibits high accuracy. ● The mean average error (MAE) of the hybrid model is 71.17 m^3/min lower than that of ANN models.	[90]
BFG	Quantile regression-based echo state network ensemble (QR–ESNE)	● The QR–ESNE method exhibits strong robustness and generalization when modelling the industrial data with high-level noises and outliers. The root mean square error (RMSE) of the QR–ESNE method is 19.84–24.96 while that of ESN is 30.82–47.32.	[91]
Gas flow	Material flow-based moving average method	● Productivity of material flow was considered. ● The method is appropriate for formulating a long-term production plan.	[22]
Gas flow	Genetic algorithm optimized support vector Machine (GA–SVM)	● The gas flow of an annealing furnace was predicted. ● Combination of GA and SVM made the model accuracy more than 95%.	[87]
Oxygen	Multiple linear regression models, and oxygen balance models	● The average relative error is $< 1\%$. ● The hit rate is 97.14% when the relative errors are within 5%.	[92]
Steam flow	Bayesian ESN models	● Combination of Bayesian theory with ESN via avoiding over-fitting in the training process. ● Baosteel CDQ turbine data showed the validity and practicality. The mean absolute percentage error (MAPE) of the Bayesian ESN is 1.06%–2.36% while that of ESN is 1.80%–4.12%.	[93]
All energy flows	Autoregressive integrated moving average (ARIMA) method	● ARIMA (1,0,0) × (0,1,1) was the best fitted model for energy consumption, with the MAPE of 0.221. ● Further integration of different techniques may lead to more efficient forecasting.	[83]
All energy flows	Seemingly unrelated regression method	● The energy intensity was predicted on a yearly basis. ● Energy consumption level is sensitive to energy price changes.	[85]

Table 4
Summary of energy flow optimization and scheduling models.

Energy flow types	Objectives	Constraints	Methods / algorithm	Benefits	Refs.
COG, BFG and LDG	Minimization of total cost	● Material and energy balances for holders and boilers ● 40,000 m^3 ≤ gas holder level ≤ 100,000 m^3 ● Process steam and electricity demand satisfaction ● 0 ≤ gas input to boiler ≤ 84,000 m^3/h	MILP	The total cost reduced by 10.42%.	[100]
Gas flow	Maximization of total steam generation	● 0 ≤ gas consumption ≤ amount of remaining gas resource ● 32.5 t/h ≤ evaporation capacity ≤ 242 t/h ● Change in gas consumption ≤ 0.5 × current gas consumption	Dynamic programming method with a reduced state space algorithm	An extra 1200 t of steam was generated in the 48-h online validation case.	[96]
Gas flow	Minimization of total cost and maximization of electric power generation	● Mass and volumetric balances in gas holders and boilers ● Mass and energy balance in the boilers and turbines ● Gas holder constraints: 35,000 m^3 ≤ BFG ≤ 150,000 m^3, 8,000 m^3 ≤ COG ≤ 40,000 m^3, 12,000 m^3 ≤ LDG ≤ 80,000 m^3 ● Logic and auxiliary equations	MILP	An increase of 0.53% in electricity generation and a potential of 9.83% achieved by operating at lower mean values of the gas holder levels	[97]
Oxygen/nitrogen	Minimization of the oxygen/nitrogen diffusion	● Device-related constraints ● 80% ≤ oxygen/nitrogen generation ≤ 105% ● 60% ≤ liquefying capacity ≤ 100% ● 10% ≤ liquid tank level ≤ 95%	MILP	The diffusion rates of oxygen and nitrogen were close to 0 after 3-h operation.	[95]
Power flow	Maximization of net profit per tonne of saleable steel	● Balance equations of capacity, material, thermal and electrical energy, oxygen ● Constraints of yields, product routes, net realizations, variable costs, and market demands ● Power load constraints. 1 MW ≤ finishing mills ≤ 3 MW; 6 MW ≤ primary mills ≤ 8 MW	MILP	The round-the-clock implementation of the model increased the net profit per tonne of saleable steel by 58%.	[101]
Steam flow and power flow	Minimization of the total operational cost	● Surplus byproduct gas consumption constraints: 0 ≤ BFG ≤ 60,000 m^3/h, 0 ≤ COG ≤ 100,000 m^3/h ● Steam consumption constraints: 0 ≤ boiler ≤ 260 t/h, 0 ≤ CDQ ≤ 120 t/h ● Power constraints: 0 ≤ steam turbine ≤ 50 MW, 0 ≤ CDQ ≤ 50 MW. ● 0.2796 RMB/kWh ≤ Price of purchased electricity ≤ 0.7188 RMB/kWh	Improved particle swarm optimization (IPSO) algorithm	A reduction of 6% in cost was achieved.	[102]
All energy flows	Exergy loss minimization and coke ratio minimization	● Balance constraints of mass and energy ● Operating constraints: 180 kg/t ≤ coke load ≤ 500 kg/t, 90% ≤ iron content in hot metal ≤ 100%, 3.5% ≤ carbon content in hot metal ≤ 4.5%, 200 °C ≤ blast furnace top gas temperature ≤ 250 °C, bosh gas index ≤ 64.78 m/min	Sequential quadratic programming	The exergy loss obtained from the exergy loss minimization and coke ratio minimization decreases by 5.77% and 5.14%, respectively.	[94]

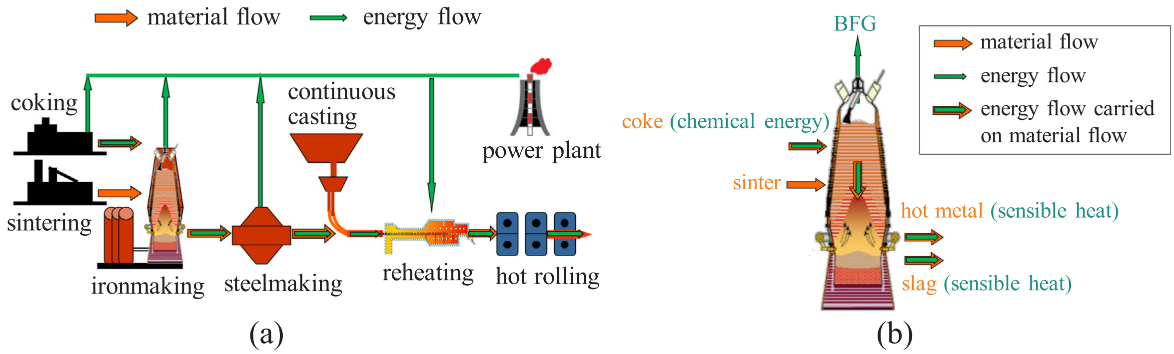

Fig. 9. Interrelation between material and energy flows. (a) site-level; (b) facility-level.

been investigated by simulation [99]. Table 4 summarizes the energy flow optimization and scheduling models in the iron and steel industry in more detail. Similar to the forecasting methods, most of the energy flow scheduling models do not consider the influences of material flow or equipment status. Moreover, the assumption that the energy flow to be allocated is always sufficient in amount is usually used in the models. However, a short-time energy flow shortage is a common phenomenon. Therefore, further work is suggested to be carried out in terms of the replacement of energy flow when it is too scarce to support material flow for production [18].

3.3. Interrelation between material and energy flows

Energy is usually used in the displacement, physiochemical conversion, deformation and phase change of materials in various iron and steel manufacturing processes [33]. It is important to clarify the interrelation between material and energy flows.

From a site-wide perspective, material and energy flows are interconnected. Based on a flow track, as shown in Fig. 9(a), energy flow runs along with material flow in some paths, but it is separated from material flow at some other nodes in the network [23]. When material and energy flows run together, they influence and interact with each other. When running in a separated way, they perform their individual features. From a plant- or facility-level perspective, material and energy flows enter the plant or facility separately, or part of the energy flow is carried by the material flow, as shown in Fig. 9(b). Inside the plant or facility, material flow interacts with energy flow to finish the production process. At the output terminal, material flow leaves the plant or facility with part of energy flow carried, while different forms of secondary energy flows can be exported separately. Yu et al. [103] and Na et al. [104] pointed out that adjusting the product structure is very important for improving energy efficiency, highlighting the importance of the interaction and synergy between material and energy flows [105].

The synergy between material and energy flow is a crucial topic, which has the potential to further reduce energy consumption and improve the energy efficiency of iron and steel production processes [33]. Hot sinter and pellets should be cooled to ambient temperature before being sent to BFs because of the temperature restrictions imposed by the feeding system and furnace roof of BFs. The sensible heat carried on them cannot enter the BF together with the hot sinter and pellets. Thus, a heat recovery facility is needed to convert the excess process heat to steam or electricity to save energy [106]. In this regard, the synergy between material and energy flow is embodied in the recovery of excess heat carried on the hot sinter and pellets. In contrast, sensible heat carried on the hot metal, molten steel, and casting slabs can be sent to the next procedure, along with the material flows. As such, the synergistic effect between material and energy flow is reflected in the utilization of process heat carried on the material flows by the next procedure. For example, the sensible heat and chemical energy of hot metal can be synergistically used in the BOF [107], and the sensible heat carried on casting slabs can be efficiently used by a reheating furnace for a synergetic purpose [7,59].

4. Challenges and future directions

4.1. Fundamental understanding of material and energy flows

The review of existing literature shows that methods and technologies previously used in the iron and steel industry are mainly based on static and individual optimization of material and energy flows. Thus, in order to further improve the energy efficiency of steelmaking, new theories, technologies and management tools are needed for synergistic operation of material and energy flows [108].

"Quantity", based on the first law of thermodynamics, is always used in this field to measure material and energy flows, either for supply or demand [109]. However, the "quality" of material and energy flows at the site level for integrated steelmaking sites is less discussed. Actually, the qualities of material and energy flows greatly influence their quantities and are crucial to the whole network. For example, the grades of ores determine the amount of hot metal produced, and the cleanliness of molten steel influences the energy intensity of the refining process. The concept of exergy, based on the second law of thermodynamics, indicates that "quality" plays a more important role in assessing the usefulness of energy [110]. Exergy has been applied to several industrial sectors and is becoming a powerful strategy to evaluate the real efficiency of a process [111]. Exergy analysis has been used in steelworks to analyze some specific energy conversion processes and has demonstrated benefits when compared with general energy analysis [112]. However, it has not been used for the entire iron and steel production site for optimizing the material and energy flow networks. Thus, it is necessary to use the concept of "exergy" in steelworks to identify specific processes or plants that have large exergy losses.

Although there have been many studies conducted on the optimization and scheduling of material and energy flows in the steel and energy fields, less attention has been paid to the material and energy flow mechanisms in steelworks, except for the analysis on flow paths and flow directions. More work should be conducted to identify the flow patterns and quantify the changes of material and energy flows throughout their conversion, transmission, storage, usage, recovery and reuse in processes. Two approaches used in fluid mechanics to track the motion of fluid, namely, the Euler approach and the Lagrange approach [113], provide good references to the description of material and energy flows. The Euler approach has been widely used in existing studies to analyze the production or consumption of material and energy flows of a specific facility (e.g., in coke ovens, blast furnaces, and reheating furnaces). The properties of material and energy flows (e.g. temperature, pressure, velocity, heat value, etc.) are described as functions of space and time. However, the Euler approach is not suitable for investigating the life-cycle flow behavior of a specific energy carrier from its generation to the end use. For instance, the consumption of BFG in reheating furnaces is directly influenced by the working conditions of reheating furnaces, but is also influenced by the generation of BFG in blast furnaces and the consumption of BFG in other users, which are difficult to be described by the Euler approach. By contrast, using the Lagrange approach, the properties of material and energy flows are able to be determined by tracking the properties of flows as they move in time. Thus, more attention should be paid to the motion behaviors of material and energy flows by using the Lagrange approach in the future.

4.2. Dynamic assessment, utilization, recovery, scheduling, and optimization

The reviewed publications show that much work has been done on the static planning of material and energy flows, but less work on dynamic optimization, especially for energy flow. In developing dynamic material and energy flow models, a major obstacle is the absence of data. A lot of data are initially collected and used for other purposes rather than scheduling material and energy flows, and some data are considered as commercially confidential. Absent or incomplete data make it difficult to investigate the optimization of material and energy flows from a dynamic view. Therefore, most studies are conducted at the static level, and a small number of studies on dynamic optimization still remain in the dynamic balancing of material and energy flows. In fact, the iron and steel production processes are more complex than that described by the existing simplified models [114]. In the future, the dynamic models of material and energy flows can be improved substantially if adequate monitoring instruments and necessary data are available. In this case, some key issues that are difficult to be solved at present can be addressed, including (1) optimal maintenance plan of the whole site considering both energy consumption and environmental emissions, (2) optimal scheduling of material flow in various continuous facilities with parallel operation, (3) coordination of the production rhythm of several batch-type facilities, and (4) accurate prediction of instantaneous amounts of energy supply and demand.

In addition, the assessment of the dynamic volatility of material flow and energy flow has not been studied in detail, although many researchers have reported the importance of quantifying flow volatility [115]. Therefore, an index for assessing the volatility degree should be figured out, based on which the effects of flow volatility on the energy efficiency and energy intensity can be studied.

The iron and steel industry is energy-intensive and most production processes operate at high temperatures. Therefore, large amounts of heat are generated, transferred, utilized, and then dissipated. Nevertheless, heat flow is insufficiently studied compared to gas, water and power flows. In iron and steel production processes, the temperature of heat flow goes up and down along its flow path [33]. Consequently, it is crucial to investigate the heat flow pattern and its dynamic migration characteristics to decrease heat dissipation and improve the energy efficiency. Waste heat recovery is another critical issue. Zhang et al. [8] highlighted that the waste heat recovery potential for a steelmaking site with the crude steel output of 10 Mt/a is 4.87 GJ/t, equal to 26.08% of the total energy consumption. Besides technologies with high conversion efficiency for high- and medium-temperature waste heat [116], it is also worthwhile to utilize low-temperature waste heat [117]. Given that different technologies use heats at different temperature ranges, it will be of great potential to implement concurrent technologies combined by two or more waste heat recovery methods [65], especially under the condition of fluctuant waste heat flow supply with dynamically changing temperature or flow rate, to achieve the most energy-efficient scheme.

Moreover, the model for reasonable energy flow dispatch is still lacking. The existing models only focus on quantitative allocation and have been built on the premise of a fixed source–sink matching relation. No literature has discussed the rationality of the source–sink matching pairs. An optimization by considering the interchangeability [118] of energy flows at the site-level is an option to determine which energy flow should be allocated to which energy consumer at what flow rate. This includes two key issues, namely, the dispatch of various energy flows among rigid energy users and the dispatch of surplus energy flow between buffers and storage units, as shown in Fig. 6.

4.3. Synergy between material and energy flows

Study on the synergy between material and energy flows is still at its early stage, which needs further investigation. Many studies consider the energy flow network as an isolated system, and estimate the energy flow only based on the historical energy flow data, taking no account of material flow. Actually, it is the variation in material flow parameters and the change of facilities' working conditions that cause the fluctuation in energy flows [22]. Thus, a hybrid model combining the data-driven method with the synergy mechanism between energy and material flows has the potential to have good performance [90].

Although the concept of synergy between material and energy flows has been accepted by researchers [119], there is still a gap in the quantitative assessment on this topic. Specific energy consumption (SEC) is always used to assess the energy efficiency of the iron and steel production processes [120], but Morfeldt and Silveira [121] found that it is not sufficient. Currently, the framework of how the synergy between material and energy flows should be evaluated is still under development. This is one of the main directions in this field.

From a dynamic view, energy saving potential lies in the quantitative imbalance between the instantaneous generation and consumption of energy flows, the grade mismatch between the supply and demand of energy flows (e.g., high-grade energy is sometimes supplied to low-grade energy demand), and the unsynergistic operation between material and energy flows. Therefore, the optimization of material and energy flows based on the synergetic thinking is worthy of further investigation. From a wider perspective, to reduce environmental pollution and improve sustainability [122], the synergy among materials, energies, water, emissions, and cash flows will play a significant role in promoting the iron and steel industry [18].

4.4. Flexibility in production processes and energy systems

As mentioned above, iron and steel production processes are dynamic, nonequilibrium, nonlinear, irreversible, and complicated systems [33], and their energy-saving potential lies in the current imbalance, mismatch and non-synergy. Therefore, flexibility in production processes (material flow) and energy systems (energy flow) is needed in order to cope with the uncertainty and change.

Sanjeev et al. [123] defined the production process flexibility as the ability to change states. Much literature on the flexible production are available, including product mix flexibility [124], routing flexibility [125], volume flexibility [126], and expansion flexibility [127]. However, only one study was found with regard to the iron and steel production processes in terms of the transport flexibility [128]. Production process flexibility is adequate for solving several material flow scheduling problems, such as hot rolling scheduling [129], steelmaking–continuous casting scheduling [130], and ladle scheduling [131].

Energy systems also require flexibility to match the energy supply and demand which dynamically fluctuate with time. This requirement has originally been pronounced in electric power systems, in which the supply and demand need to be balanced in real time [132]. The concept of flexibility was then extended from electric power systems to other energy systems, such as heating [133] and gas networks [134]. Energy system flexibility allows for changes in energy flow generation and consumption over time and is a valuable resource when the energy flows have increasingly intermittent features. Likewise, energy system flexibility is also an important tool for the iron and steel industry, which operates in increasingly uncertain environments. The energy systems of steelworks need flexibility to adjust the generation and consumption of energy flows in response to the changes in material flow and environmental limits. Furthermore, steelworks are able to utilize their energy system flexibility to provide ancillary services for external power or heating networks to create more revenues [135]. However, only a few publications on reductant flexibility [136] and power flexibility [137] fell with the scope of energy system flexibility of steelworks, so further research in this area is needed.

As an energy intensive sector, the iron and steel industry is facing challenges of energy conservation and low-carbon steelmaking. Coal-related fuels account for 90% of the direct energy consumption of the iron and steel industry, equivalent to 83% of the total comprehensive energy consumption [115]. Therefore, the substitution of coal with other environmentally friendly energy sources, such as renewable energy or nuclear energy, will considerably reduce the carbon intensity of the industry. The introduction of intermittent renewable energy in steelworks reduces the predictability of energy flow and increases the need for flexibility in energy systems. The results of Feta et al. [137] showed that, for positive flexibility capacity (demand reduction), Tata Steel in IJmuiden is able to supply the potential of 10 MW for 15 min with an availability rate of 97%, or 20 MW with an availability rate of 65%. For the negative flexibility capacity (demand increase), it was found to be 20 MW for 30 min with the doubling of BFG storage capacities. The qualification and enhancement of positive and negative flexibility provisions of the iron and steel industry in the context of steelmaking, driven by renewable energy and nuclear energy, is suggested to be an important research domain.

4.5. Smart steel manufacturing and smart energy system

With the development of new technologies such as the Internet of Things (IoT), big data analytics, cloud computing and artificial intelligence (AI), smart manufacturing has been proposed in modern industry [138]. Smart steel manufacturing, as the application of smart manufacturing in steelmaking, is being predicted as the “Industry 4.0” for the iron and steel industry, with the cyber-physical system (CPS) as the core [139]. Currently, the main components of the CPS for steelmaking sites, such as BFs, BOFs, ladles, continuous casting slabs and hot rolled pieces, are still treated as black boxes, because information inside the reactors and products is unavailable. The physiochemical reactions inside the black boxes cannot be grasped accurately. As a future direction, “digital twins” [140] of these real-life physical objects are able to be built, as shown in Fig. 10, using the digital sensing technologies and the collected big data to describe the changes inside the black boxes.

Smart steel manufacturing includes smart energy systems, which are

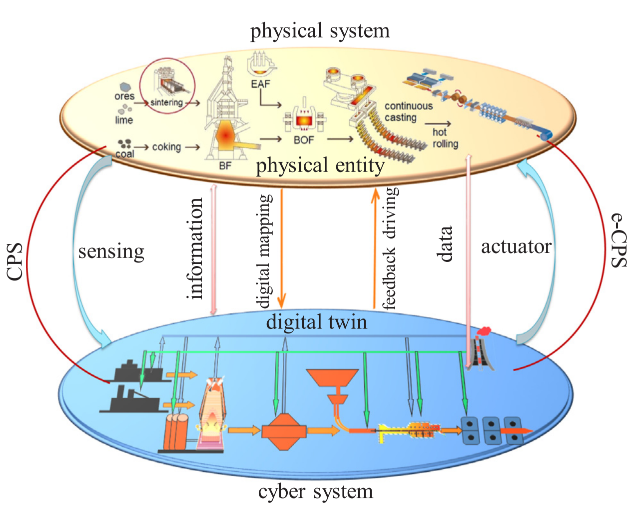

Fig. 10. CPS for smart steel manufacturing.

the so-called ‘CPS for an energy system’ (e-CPS) [141]. A smart energy system requires trusted energy flow data and information at proper times, locations and forms. Although advanced information technologies such as radio frequency identification (RFID), smart sensors and smart meters can be used in e-CPSs to collect energy flow data, it is still impossible to install instruments at all points in the physical energy system. With regard to this, state estimation is a feasible solution [142]. In addition, with a flexible energy system, steelmaking sites need to trade with external energy producers/consumers or provide ancillary services for bulk energy networks. Blockchain-based technology has been emerged as a promising solution for establishing the trading platforms in a replicable, secure, verifiable, and trustworthy way [143].

4.6. Evolutionary steelmaking routes and technologies

To cope with the growing environmental pressures and to decarbonize the iron and steel industry [144], several evolutionary steelmaking routes and technologies are presently being developed. Besides carbon capture and storage (CCS) technology [24] and the EAF route, nuclear steelmaking or hydrogen steelmaking, using DRI as the iron-bearing material, has the potential to replace the current BF–BOF route which is dominant. As shown in Fig. 11, the CO_2 reduction potential is expected to be 26% at the end of the pilot phase, 50% at the end of 2040s, and 95% at the end of the evolutionary route replacement [145]. The new route relies heavily on the access to electrical power favorably from renewable resources, on a very large scale, both for hydrogen production and EAF operation. This route replacement will cause extensive changes to existing integrated steelworks. However, little literature was found on the material and energy flow analysis and optimization of the new steelmaking routes. In addition, the challenges mentioned in Sections 4.1–4.5 also exist for the evolutionary routes and technologies, which are future research domains as well.

5. Conclusions

The contribution of this review is to provide a timely, academic-led discussion of material and energy flows of the iron and steel industry. First, this paper presented an overview of different steel production routes, including the BF–BOF route, the EAF route, and the combination of them. Next, the status quo of the material and energy flows of the iron and steel industry was presented. The selected publications contain eighty journal articles, conference papers, white papers and industrial reports, and they have been divided into three categories, namely, material flow and material flow scheduling, energy flow and energy flow network, and the interrelation between material and energy flows. The literature review shows that nearly all the material flow optimization methods were studied with the assumption of a sufficient energy flow supply. By reviewing the physical and mathematical models of energy flows, it has been seen that although there are many studies on energy flows and energy flow networks and energy consumption has been remarkably reduced based on these studies, only a few energy flow models have been established with the consideration of material flow. Actually, the material–energy nexus should not be ignored and the synergy of the two aspects is a new field that needs further research.

Material and energy flows are facing a wide variety of challenges to realize their potential and the corresponding future directions have been highlighted in the paper. Understanding of the flow mechanisms of material and energy flows in steelworks is still insufficient, especially in the uncertain environments of iron and steel production. Besides, the quality of material and energy flows, as well as their motion features, require more attention. Therefore, advanced theories in energy sciences, such as the exergy and Lagrange motion tracking approach, should be introduced to metallurgical engineering practice. The dynamic assessment, utilization, recovery, scheduling, and optimization of the energy flows in steelworks should also be studied in the future, considering the influences of the steel production rhythms on the

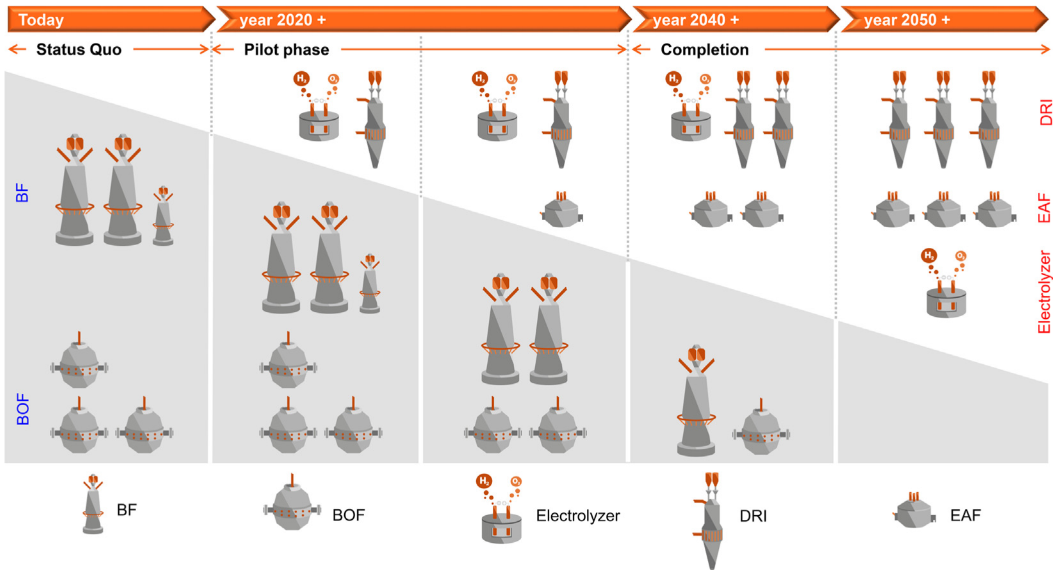

Fig. 11. Future iron and steel production route [145].

energy use. In addition, from a synergetic perspective, quantitative assessment and improvement measurements of the synergistic degree between material and energy flows in steelworks are highly recommended. With the increasing requirement of renewable energy utilization, flexible iron and steel production processes and flexible energy systems require further research. Another direction of the iron and steel industry is to develop smart steel manufacturing and smart energy systems. Finally, the challenges and prospects of evolutionary steelmaking routes and technologies have been analyzed, concluding that more work needs to be done on the analysis and optimization of material and energy flows in order to integrate the evolutionary solutions into integrated steelworks.

Declaration of Competing Interest

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

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