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Review

Energy saving technologies and mass-thermal network optimization for decarbonized iron and steel industry: A review

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ABSTRACT

The iron and steel industry relies significantly on primary energy, and is one of the largest energy consumers in the manufacturing sector. Simultaneously, numerous waste heat is lost and discharged directly into the environment in the process of steel production. Thus considering conservation of energy, energy-efficient improvement should be a holistic target for iron and steel industry. The research gap is that almost all the review studies focus on the primary energy saving measures in iron and steel industry whereas few work summarize the secondary energy saving technologies together with former methods. The objective of this paper is to develop the concept of mass-thermal network optimization in iron and steel industry, which unrolls a comprehensive map to consider current energy conservation technologies and low grade heat recovery technologies from an overall situation. By presenting an overarching energy consumption in the iron and steel industry, energy saving potentials are presented to identify suitable technologies by using mass-thermal network optimization. Case studies and demonstration projects around the world are also summarized. The general guideline is figured out for the energy optimization in iron and steel industry while the improved mathematical models are regarded as the future challenge.

Contents

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Nomenclature

C	Specific heat ($kJ \cdot kg^{-1} \cdot K^{-1}$)
T	Temperature (K)

Abbreviations

AC	Activated carbon
BF	Blast furnace
BFG	Blast furnace gas
BOF	Basic oxygen furnace
COG	Coke oven gas
CCS	CO_2 capture and storage
CDQ	Coke dry quenching
CHP	Combined heat and power
CMC	Coal moisture control
DC	Direct current
DRI	Direct reduced iron
EAF	Electric arc furnace
ECOARC™	Ecological and economical high-efficient arc furnace
EIP	Eco-industrial park
FB	Fluidized bed
GAX	Generator-absorber heat exchange
KC	Kalina cycle
LDG	Linz-Donawitz gas
MDEA	Methyldiethanolamine
MSP	Membrane separation process
ORC	Organic Rankine cycle
PCI	Pulverized coal injection
PCM	Phase change material
PRA	Pre-reduced agglomerates
PSA	Pressure swing adsorption
SCOPE21	Super coke oven for productivity and environmental enhancement toward the 21st century
SSW	Segregation slit wire
TEG	Thermoelectric generator
TRT	Top pressure recovery turbine
VSD	Variable speed drive

Subscripts

HM	Hot metal
DRI	Direct reduced iron

1. Introduction

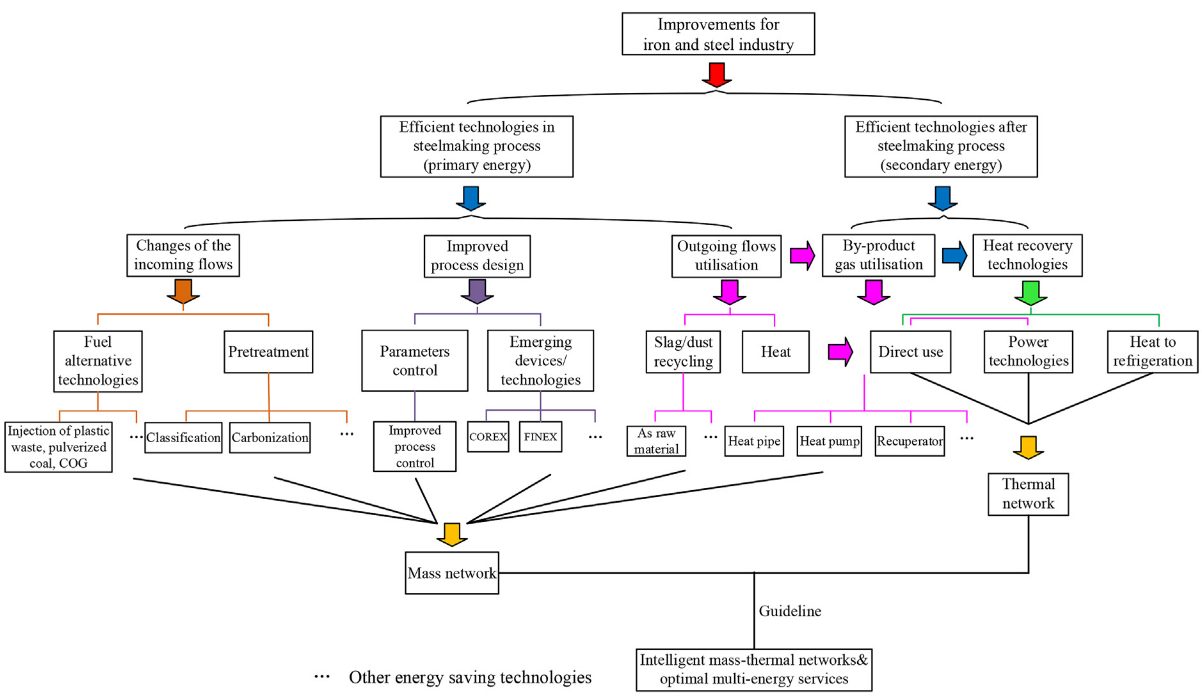
Iron and steel production is considered as a key index of national prosperity and plays a leading role in the world economy. The sector employs high temperature furnaces for iron and steel production, which has become the second largest energy consumer in industry (Department of Energy, 2008). Driven by increases in crude steel production, the sector's energy consumption grew by 6.2% annually from 2000 to 2011 (IEA, 2014). Besides, carbon dioxide (CO_2) emissions from plants of iron and steel account for the highest proportion of about 27% in manufacturing sector (IEA, 2007). Iron and steel has achieved considerable improvements in recent decades, however, it still reveals great potentials to further reduce energy use and CO_2 emissions by about 20%, i.e. saving 4.7 EJ of energy and 350 Mt of CO_2 (Ma et al., 2012; Ouyang and Lin, 2015). These improvements could be achieved by saving energy during or after the manufacturing processes. Accordingly, primary energy and secondary energy will be illustrated based on the mass network and thermal network for further optimization.

Considering primary energy, most of fossil fuels are consumed in the iron and steel production processes where the coking coal has a major proportion of energy use (Sarna, 2014). In 2017, three quarters of energy use in iron and steel industry comes from coal (IEA, 2019). Furthermore, the actual resource efficiency of global steel production is only 32.9% due to a large number of energy losses (Gonzalez Hernandez et al., 2018b). With rapidly rising price of primary energy, it is quite significant to further improve energy efficiency which could reduce fossil fuel consumption and global CO_2 emissions in iron and steel industry (Siitonen et al., 2010; En et al., 2014). Various energy saving technologies/measures are adopted to reduce usage of primary energy in steel plant. These potential improvements include composition regulation of incoming energy flows, adjustment of energy-related processes, and utilization of outgoing flows in the iron and steel industry (Johansson and Söderström, 2011). Although the efficient energy utilization has been partially achieved by various researches during the past decades, the average efficiency has not been substantially increased (IEA, 2007). In the future, the deployment of energy saving technologies is still critical for iron and steel making (Hasanbeigi et al., 2014). These technologies ultimately aim to reduce the energy demands in iron and steel industry and they should be optimized based on a mass network.

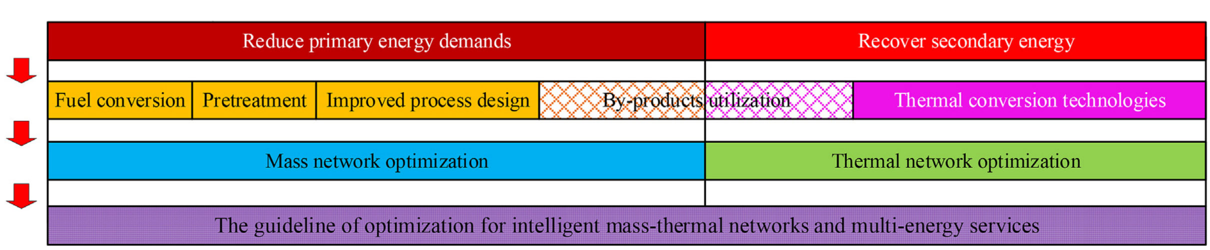
Recovery of secondary energy is the other considerable energy saving option. The secondary energy in iron and steel enterprises is mainly composed of by-products (Zhao et al., 2017) and waste heat (Jouhara et al., 2018). A large amount of outgoing excess gases such as coke oven gas (COG), blast furnace gas (BFG) and Linz-Donawitz gas (LDG) are generated from steelworks (Zhang et al., 2010), which account for approximately 30% of total energy consumption in steel enterprises (Zhao et al., 2017). These resources could be efficiently used as fuel or to generate power and heat (He and Wang, 2017). BFG with high pressure is recycled to generate electricity through top pressure recovery turbine (TRT) technology (Johansson and Söderström, 2011). There is great interest in reusing these gases to synthesize high-added value products e.g. COG as a potential feedstock for H_2 separation, CH_4 enrichment and methanol production (Uribe-Soto et al., 2017; Xu, J. et al., 2018). It is evident that by-product gas or slag is the medium that could either be directed used or transferred into thermal energy which belong to mass or/and thermal network.

With regard to waste heat in the steel mills, currently only about 25% of residual heat is recovered by a few commercial technologies (Jouhara et al., 2017). Thus further improving the energy efficiency of waste heat utilization is still of great value. Various thermal conversion technologies could be good candidates in terms of heat supply/storage, power generation and refrigeration. Heat supply and storage could be achieved by heat exchanger and storage reactor. Heat exchangers are most commonly used to transfer heat from combustion exhaust gases to the other place where the heat is needed (Ma et al., 2017). The common thermal driven power generation cycles are Rankine cycle, organic Rankine cycle (ORC) (Ramirez et al., 2017), Kalina cycle (KC) (Wang et al., 2017), thermoelectric cycle (Zare and Palideh, 2018) and so on. Thermal driven refrigeration could be generally classified into absorption (Ullah et al., 2013), adsorption (Askalany et al., 2017), and thermoelectric refrigeration (Pietrzyk et al., 2016) which could meet cooling demands for office building in steel mill. It is extensively acknowledged that the demands for waste heat recovery technologies should not only supply the heat but also work as power, refrigeration and energy storage in a district. The integration of various energy types should be taken into account when each kind of technology is ensured. The utilization and selection of technologies are quite complicated if various heat sources and different demands are required to be satisfied (Konstantelos and Strbac, 2018). It is demonstrated that high-quality integration of different technologies should be accomplished to realize high efficient use of industrial waste heat through thermal network utilization, which includes heating, power generation, cooling, energy storage and transportation (Ayele et al., 2018).

From previous work, the energy saving in iron and steel industry mainly concentrates on the primary energy in terms of different operation processes. It could provide more insights if the primary and secondary energy saving technologies could be effectively related and optimized as a network. In this paper, the concept of mass-thermal network optimization in iron and steel industry is presented and summarized. Essentially, mass network



(a)



(b)

Fig. 1. Roadmap of efficient use of energy in iron and steel industry (a) main concepts; (b) general summarization.

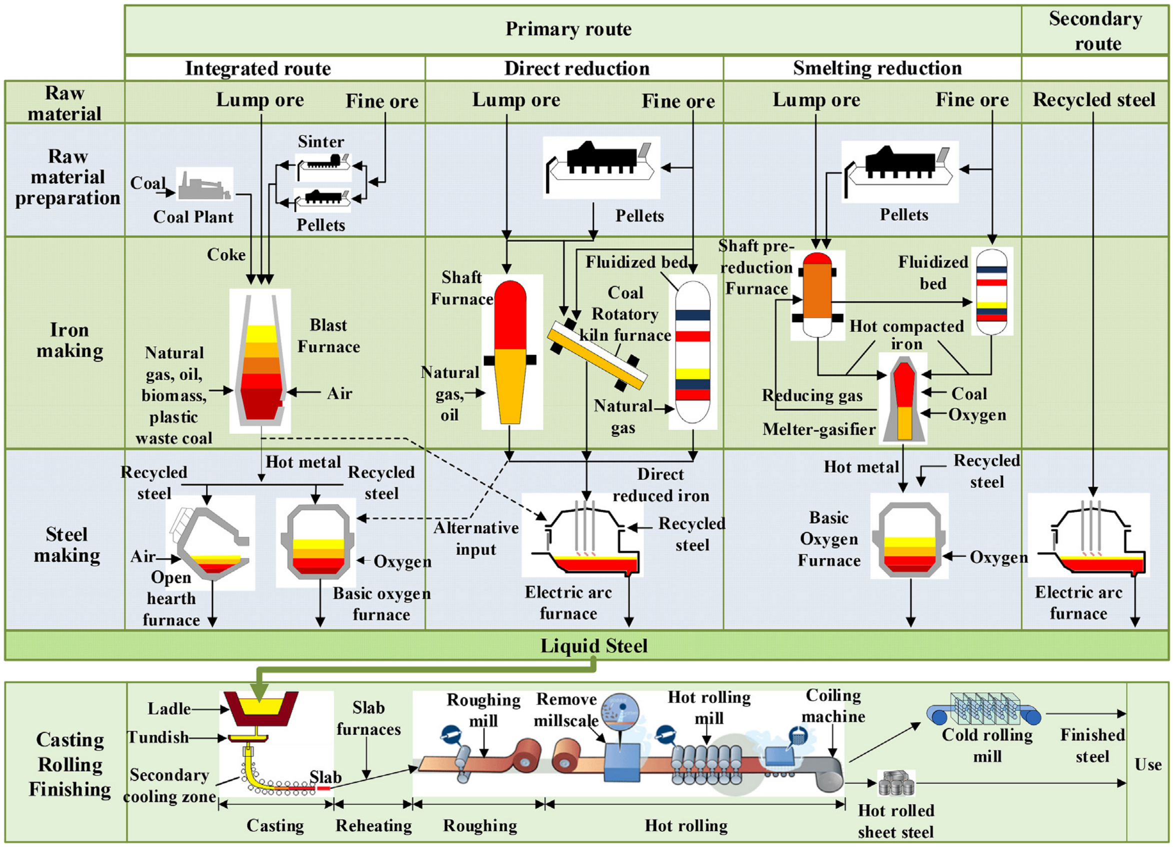


Fig. 2. Iron and steel production routes, adapted from references (Industrial Efficiency Technology Database; Uribe-Soto et al., 2017).

optimization lies in the reduction of demands whereas thermal network optimization relies on the supply sides for energy savings which are dependent and independent. The general guideline of optimized mass-thermal network in iron and steel industry is finally summarized which may achieve an energy saving target from an overall perspective. To further clarify the framework of this paper, the concerning roadmap of efficient use of primary and secondary energy is indicated in Fig. 1, in which Fig. 1a represents main concepts of energy, improvements and mass/thermal optimization while Fig. 1b generally summarizes and clarify their classifications for the readers.

2. Description of iron and steel industry

2.1. Iron and steel metallurgical routes

It is extensively recognized that steel is essential to current technologies and economic activities that meet daily demands of our society (World Steel Association, 2012). Fig. 2 shows an overview of iron and steel metallurgical routes which will be briefly introduced in the rest of this subsection. The iron and steel production processes are composed of two basic routes: (1) primary route where iron ores and scrap are used as the raw materials, (2) secondary route from recycled steel scrap (Napp et al., 2014; Quader et al., 2015).

Primary steel production route includes raw material preparation, iron making, and steel producing processes. The blast furnace (BF) and basic oxygen furnace (BOF) integrated process accounts for the most crude steel making, which is approximately 64% of the global steel production (González and Kamiński, 2011). BF-BOF route consists of sintering, pelletizing, coking, iron making and steel making processes. Sintering and pelletizing are two main processes. They are related with treatment of iron ores and minerals that will be used for subsequent iron making in BF (Jamison et al., 2015). Coke is a necessary raw material used in the BF, which is a chemical reductant and a permeable support to allow gases through the furnace (Worrell et al., 2010). In the iron making process, coke is reacted with the sinter or pellet ore in the BF, which results in molten iron product i.e. pig iron (Jamison et al., 2015). The carbon impurities and concentration of alloying elements of iron product are removed in the BOF process. Open hearth furnace is an energy-intensive steel making technology and has nearly been phased out (Quader et al., 2015). Direct reduction and smelting reduction are two technologies that offer alternatives to BF-BOF for

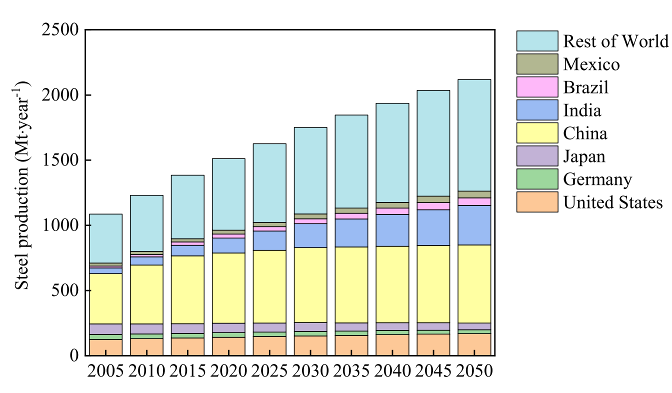


Fig. 3. World steel consumption in various regions (World Steel Association, 2012).

iron making. Two processes could not consider the demand for the energy-intensive products, i.e. coke and sinter (Worrell et al., 2010). The iron from the direct reduction route is fed into the electric arc furnace (EAF) steel making process.

In the secondary route i.e. EAF, the recycled steel scrap is melted by using high power electric arcs. Since there is no raw material preparation and iron making steps, EAF has much lower energy consumption (Worrell et al., 2007). For the long-term perspective, substituting BOF steel making with EAF is a reasonable solution to energy conservation and cost control. Although plenty of the electricity used for EAF may be supported by coal-fired power plants, iron and steel industry will be less dependent on coal due to the reduction in BF-BOF production, which contributes to lower energy intensity and greenhouse gas emissions (Energy Information Administration, 2016).

After steel production, the process is followed by continuous casting production and rolling. The molten steel will be transferred to the continuous caster where the semi-finished steel products are formed. Before entering the market, most steel products are further processed to form final shapes in the rolling mills. Rolling mills consume electricity and fossil fuels in furnaces which are used to reheat the steel before rolling (Hasanbeigi, 2013). Finishing is the final production step that includes different processes which are annealing, pickling, and surface treatment (Price et al., 2002).

2.2. Overarching energy use in iron and steel industry

Global crude steel production climbs with the increase of the demands, which has grown by seven times since 1950 and it is expected to increase by 1.5 times before 2050 (World Steel Association, 2012). As shown in Fig. 3, developing countries in Asia e.g. China and India account for major proportion of this growth. Inevitably, the continuous increase in steel production and consumption will bring about an increase in the industry's energy use (Hasanbeigi, 2013).

In 2017, the total energy demand of iron and steel sector grew to 33.44 EJ, which accounted for 21.4% of final energy consumption of the world industry (IEA, 2017). The proportions by using fuels in world iron and steel sectors are presented in Fig. 4. It is indicated that coal serves as the primary fuel to generate coke and power, which accounts for the largest part (around 75%) (He and Wang, 2017; IEA, 2017); 9% of the final energy is consumed by natural gas which can effectively power the process especially in the direct reduced iron (DRI) production; the rest of energy consumption comes from secondary energy i.e. electricity (12%), heat (3%), and other fuel gas and oil products.

Fig. 5 indicates the energy input of main steel producing countries. It is noted that different countries have different energy distributions in the steel production routes. The iron and steel industry in China consumes the most fossil fuel i.e. coal and produces 94.1% of crude steel through the BOF route. Comparably, crude steel production in United States mostly adopts EAF steel making route (62.7%) and natural gas (53.98%). This is mainly because mature and

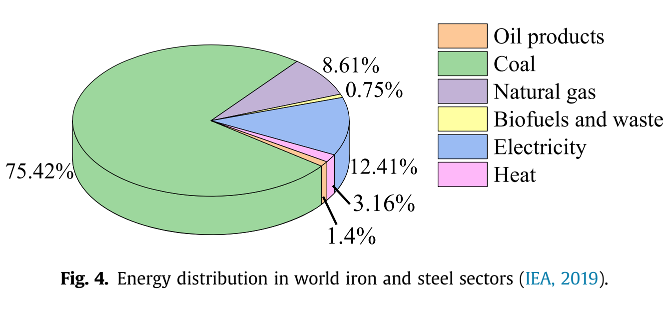


Fig. 4. Energy distribution in world iron and steel sectors (IEA, 2019).

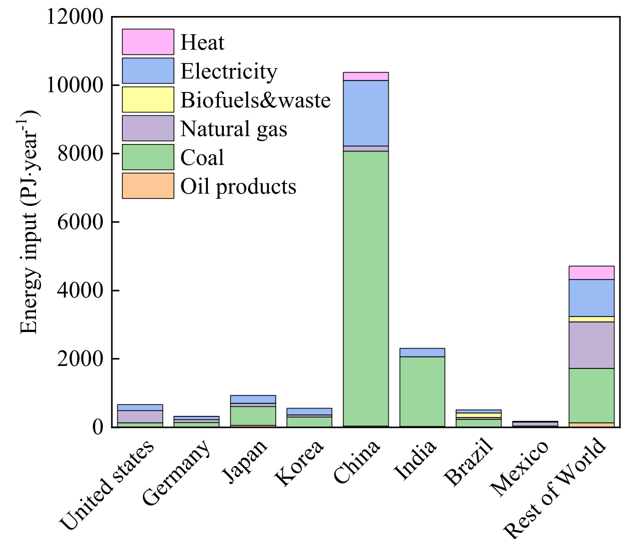


Fig. 5. Energy input of main steel producing countries in 2015 (IEA, 2015).

industrialized economy supplies a large scrap steel for EAF steel making in United States. Since India is rich in coal resource and has limited source of natural gas, coal-based DRI is a leading way to supply the feedstock for EAF (Morrow et al., 2014). In other countries, their use of electricity or natural gas is nearly related to the share of EAF steel production.

In 2015, the aggregated global energy intensity dropped slightly to 20.9 GJ$\cdot$t^{-1} crude steel from 21.1 GJ$\cdot$t^{-1} in 2010 (IEA, 2019). Considering main production processes, energy use by BF-BOF route is estimated as 18.7 GJ$\cdot$t^{-1} crude steel. The typical energy consumption of DRI-EAF pathway is about 22.4 GJ$\cdot$t^{-1} crude steel. The energy intensity of smelting reduction to BOF processes is about 21.4 GJ$\cdot$t^{-1} crude steel. The scrap-based EAF has the lowest energy footprint of 6.7 GJ$\cdot$t^{-1} crude steel. By adopting best available technology, energy performance levels worldwide in all steel production routes would save 9 EJ per year (IEA, 2017).

Energy efficiency policies of iron and steel industry have led to the partial retrofit of existing furnaces with energy-efficient equipment. The iron and steel sector still has vast technical potentials to further reduce energy consumption by around 20% (IEA, 2012). Fig. 6 presents the estimated energy saving potentials based on current production capacities and technologies. The average global energy saving potential is 4.3 GJ$\cdot$t^{-1} crude steel and China accounts for 70% of potential energy savings. Most of this potential could be realized by improving BF and steel finishing processes as well as recycling steelworks by-product gases. Electricity production from BFG offers an important opportunity for steel plant to maximize the usage of input fuels (IEA, 2014).

3. Efficient technologies for primary energy

The primary energy is the largest component of operating cost for many steel producers (Yellishetty et al., 2010), thus the primary energy saving opportunities should be assessed based on actual energy demands. It is of great importance to consider the efficient technologies in aspect of mass balance i.e. mass optimization. The technologies can be manifested in the incoming and outgoing flows of a plant, as well as the specifications of the installed facilities. The detailed analysis of efficient technologies for primary energy is conducted in terms of specific energy savings and investment cost which are demonstrated as follows.

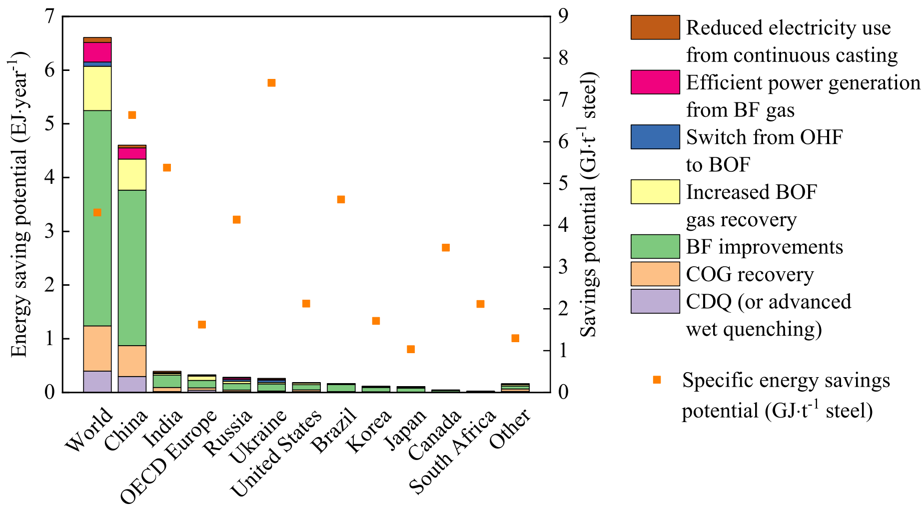


Fig. 6. Energy saving potentials for iron and steel industry based on best available technologies (published in 2014) (IEA, 2014).

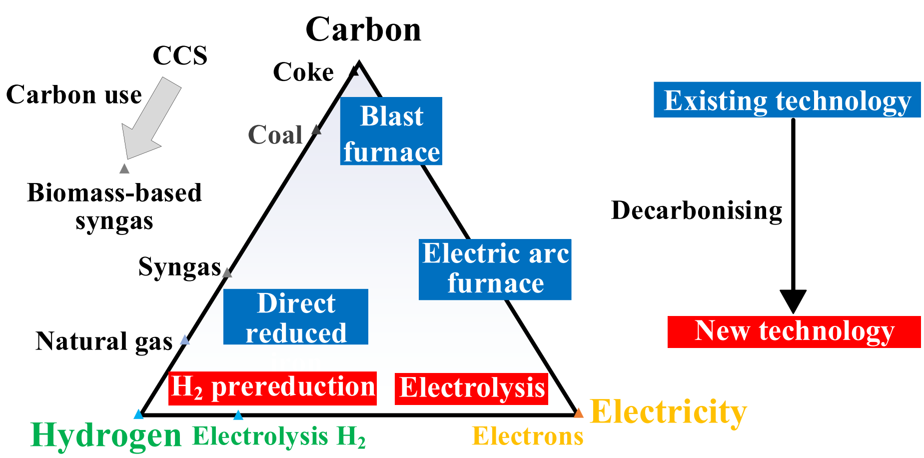


Fig. 7. Framework of steel triangle processing route (Sadoway, 2008).

3.1. Changes of the incoming flows

The direct input of raw materials and energy for each process and facility are included in the incoming flows of iron and steel industry. Energy saving technologies for incoming processes mainly refer to energy substitution and pretreatment of feedstock, which generally tend to reduce consumption of fossil fuels and raw materials. Energy substitution aims to replace fossil fuels with cleaner energy and to increase the share of renewable resources (Wang and Lin, 2017). Pretreatment of feedstock is considered as a good way to enhance productivity of each plant.

3.1.1. Fuel substitution technologies

The consumption of coal-dominated energy in the iron and steel industry has undermined sustainable development (Wang and Lin, 2017). The energy sources of steel production processes needs to shift from coal to natural gas, hydrogen, electricity, biomass and so on. (Fujii and Managi, 2013). Various approaches are summarized and presented in Fig. 7. It is demonstrated that iron and steel production has been gradually decarbonized by reducing the use of coal, which would be partially replaced by natural gas, oil, plastic waste, hydrogen, electricity, integration with CO_2 capture, utilization and storage technology and sustainable biomass technology (Sadoway, 2008; Birat, 2010).

To reduce expensive coke consumption and CO_2 emission in coke making process, pulverized coal injection (PCI) has been widely used as the auxiliary fuel in the BF process. Finely ground dried coal is injected with gas into BF through the tuyère as a partial replacement for the coke (New Energy and Industrial Techonology Development Organization, 2008), which will decrease the coke ratio of the BF and improve the net energy efficiency (Oda et al., 2007). Similar to PCI, natural gas injection could substitute part of coke, but it is typically applicable to medium-sized furnaces which usually have an annual production rate of 1.4–2.5 million tons of iron (Jones, 2012). Besides, natural gas and pulverized coal can be simultaneously injected into BF tuyères by using a combined fuel lance (Majeski et al., 2015). The injection of oils and waste oil is beneficial, which is similar with the natural gas injection. The amount of injected oil is within the range of 65–130 $kg \cdot t_{HM}^{-1}$ (European Integrated Pollution Prevention and Control Bureau, 2010). It is desirable to reuse waste plastics for the better utilization of energy resources due to their higher heating values and higher H_2 contents when comparing those with coal (Chu et al., 2004). The maximum level for plastic injection at the tuyères level could reach 70 $kg \cdot t_{HM}^{-1}$ (European Integrated Pollution Prevention and Control Bureau, 2010). H_2 can react with iron ore to achieve reducing coke and above alternative reducing agents in

Table 1
List of representative fuel substitution technologies in the BF.

Fuel alternative technologies	Injection rate	Coke rate $kg \cdot t_{HM}^{-1}$	Ref.
PCI	$190-210\ kg \cdot t_{HM}^{-1}$	280–300	Nomura and Callcott (2011)
Natural gas injection	$96-158\ m^3 \cdot t_{HM}^{-1}$	341–410	Halim et al. (2009)
Heavy oil injection	$140\ kg \cdot t_{HM}^{-1}$	300	Cores Sánchez et al. (2009)
Plastic waste injection	$35\ kg \cdot t_{HM}^{-1} + 71\ kg \cdot t_{HM}^{-1}$ heavy oil	372	Trinkel et al. (2015)
COG injection	$50\ kg \cdot t_{HM}^{-1}$	322	Slaby et al. (2006)
H_2 injection	$27.5\ kg \cdot t_{HM}^{-1}$	389.8	Yilmaz et al. (2017)
Charging lump charcoal	$200\ kg \cdot t_{HM}^{-1}$	260	Babich et al. (2010)
Biomass-oil injection	$140\ kg \cdot t_{HM}^{-1}$	455	Ng et al. (2010)
Biomass-syngas injection	$10.5\ GJ \cdot t_{DRI}^{-1}$ for DRI production	–	Buergler and Di Donato (2009)

BF. The indirect reduction process by H_2 has the advantage of zero CO_2 emission in the produce gas (Chen et al., 2012). COG and BFG are recovered as supplementary fuel in most of steel plants. Various combustion processes could reuse these gases such as blast generation in hot stoves or coke oven firing (European Integrated Pollution Prevention and Control Bureau, 2010).

Burgeoning attentions have been paid to the biomass as a renewable substitute in the iron and steel industry. For the integrated steel plant, biomass has been inserted into coal compound during coke making process to produce bio-coke which is effective in reducing the gasification temperature in BF (Hanrot et al., 2009). In sintering process, the substitution of 25% coke breeze with bio-char is an suitable method to optimize productivity and quality of sinter (Mousa et al., 2015). The biomass-based reducing agents, e.g. charcoal, bio-oil, and syngas could be injected into the BF from the top or through tuyères to minimize the coke consumption (Mousa et al., 2016). Novel carbon composite agglomerates have been investigated to renovate outdated coke ovens and low reduction rate operation of BF (Anyashiki et al., 2009). The pretreatment and upgrading processes of raw biomass are required in these applications.

Table 1 reviews representative fuel substitution technologies and their potentials to reduce coke used in the BF. These results are based on the actual performance of operating BF or on mathematical modelling. Depending on the amount of auxiliary injectants, the mean coke rate of the furnace is 334 $kg \cdot t_{HM}^{-1}$, and a theoretical minimum of 200 $kg \cdot t_{HM}^{-1}$ is necessary to enable stable furnace operation (Yilmaz et al., 2017). Compared to all reductants, 200–250 $kg \cdot t_{HM}^{-1}$ coke can be replaced, which may result in lower emissions (Ghanbari et al., 2015). With the advantages of high reliability and easy operation, PCI has better performance to reduce coke consumption in BF operation. Although the usage of biomass in steel industry shows great potentials, there are still lots of challenges in terms of technical and economic aspects.

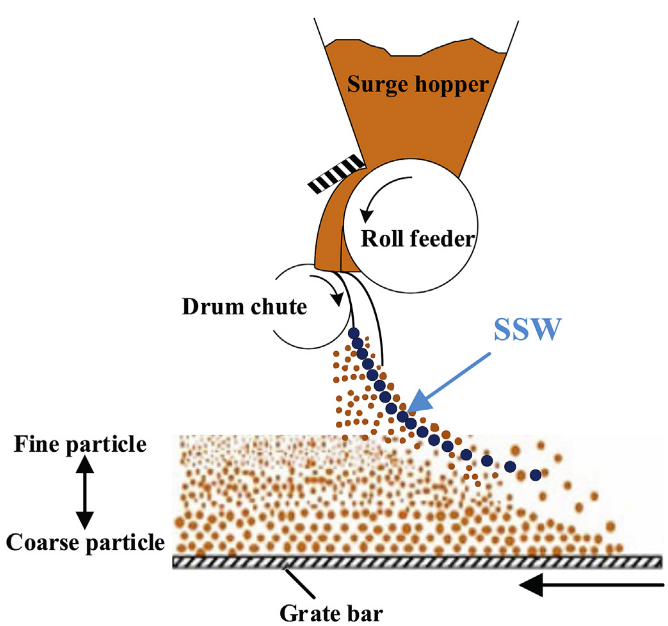


Fig. 8. Schematic diagram of segregating slit wires (Lu and Ishiyama, 2016).

3.1.2. Pretreatment of feedstock

Before charging raw materials into iron and steel works, pretreatment is always essential for the quality and purity of feedstock. The pretreatment mainly involves granulation and torrefaction, which can be classified as physical and chemical process. Physical pretreatment is used to control particle size and moisture content of raw materials. In sinter plant, new coating and granulation technologies have developed to improve sintering productivity and reducibility (Lu and Ishiyama, 2016). The segregation slit wire (SSW) system is an advanced charging system which is developed in Japan as shown in Fig. 8. It is a device to reduce coarse granule and maintain a constant particle size of limonite, which could increase permeability of the sintering mixture and reduce the return fine. In coke oven, it is proved that the densification of coals to a relative material density of 80%, i.e. a compact density around 1100 $kg\ m^{-3}$ is advantageous (Kuyumcu and Sander, 2014). The stamp charging technology is usually used to compact the coal, where the coal blends are previously compressed into a “coal cake” and then charged vertically into the oven. With stamp charging, the coke oven productivity is increased by 10–12% (Steel Authority of India Limited, 2008). For the modern BF process, controlling particle segregation to obtain a desired gas flow and smooth operation is very significant (Xu, Y. et al., 2018). Bell-less top systems are adopted for proper burden distribution and segregation of input materials into the furnace, which can enhance the furnace operational stability and increase the productivity (Paul Wurth, 2012).

The general methods to remove the moisture of feedstock include preheating and drying. Coal moisture control (CMC) was introduced to Japan in the 1980s (Radhakrishnan and Maruthy Ram, 2001), because coke making process requires the application of coal blends with a correctly matched level of moisture. This industrial application controls the moisture of feedstock for coke producing from a normal 8–10% to around 6% without hindering the charging operation (New Energy and Industrial Techonology Development Organization, 2008). The process is different from coal preheating and drying because it leads to the strict stabilization of moisture content in the coal blend. Low pressure steam and waste heat from COG are generally used as the heat source of humidity control. For instance, Nippon steel succeeded in developing the fluidized bed (FB) type CMC which exhibited high heat exchange efficiency and solved the problem of indirect heat exchange between the coking coal and steam (Nippon Steel & Sumikin

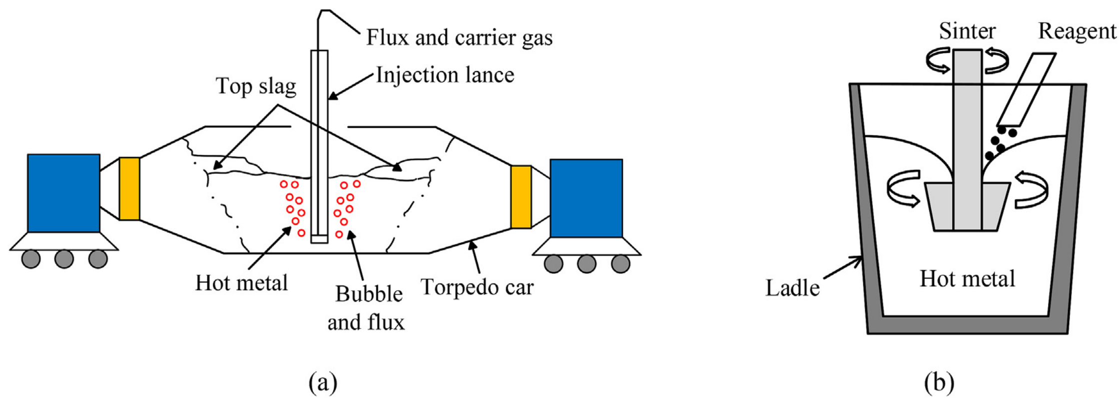


Fig. 9. The hot metal desulphurization process (a) Injection process of hot metal desulphurization using a torpedo car; (b) Mechanical stirring process for hot metal desulphurization using a charging ladle (Kitamura, 2014).

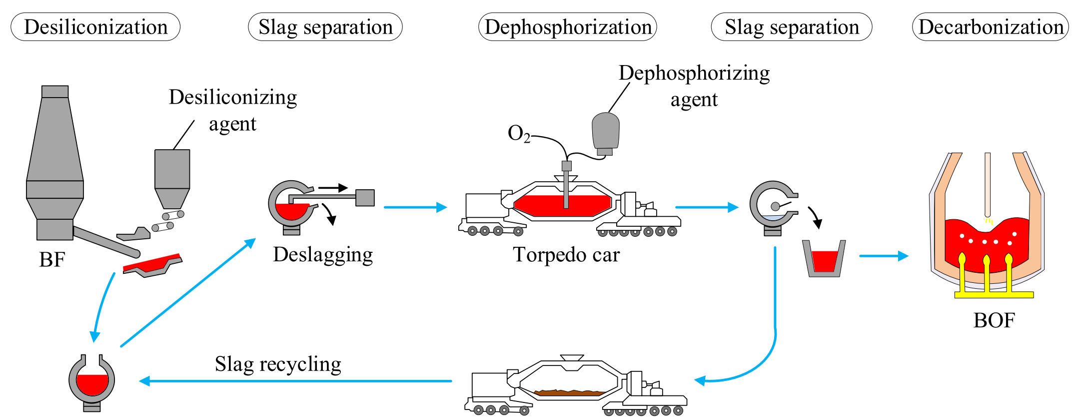


Fig. 10. Exemplified steps for desiliconization and dephosphorization of hot metal (Hasanbeigi et al., 2010).

Engineering CO., 2017).

Compared with physical process, chemical pretreatment always aims to improve the quality of raw materials that are prior to iron and steel making processes. In general, high iron content and low gangue content of sinter or pellet, and moderate ash content of coke are all good factors for BF injection (European Integrated Pollution Prevention and Control Bureau, 2010). Apart from the usual feedstock of BF, a newly developed pre-reduced agglomerates (PRA) was proposed in Japan. The PRA was reduced simultaneously with agglomeration on existing sintering machine (Machida et al., 2009). It has excellent high temperature properties to reduce pressure drop and thickness of the BF cohesive zone, which is quite conducive to BF productivity. Hot metal chemical pretreatment is a process that performs on hot metal after the tapping of BF and before decarbonization in a BOF (Kitamura, 2014). In most cases, this process is composed of desulfurization, dephosphorization and desiliconization. The general desulfurization process can be divided into flux injecting and mechanical stirring which are shown in Fig. 9. The dephosphorization and desiliconization are not as common as the desulfurization due to their costly and sophisticated

Table 2
List of selective pretreatment technologies for steel and iron industry.

Pretreatment technologies		Improvement effect	Ratio of energy savings[a]	Ref.
Burden distribution	Sinter SSW charging	Increase 5% productivity	5.6%	New Energy and Industrial Techonology Development Organization (2008)
	Coke stamp charging	Increase 10%–12% productivity	9.1%–16.7%	Madias and de Córdova (2013)
	Bell-less top BF	Increase 2.5% productivity	2.4%	Radhakrishnan and Maruthy Ram (2001)
Coke moisture control		Increase 2% coke strength	0.72%	(Jones, 2012; Cui et al., 2015)
PRA in BF		45% pre-reduction	23%	Machida et al. (2009)
EAF charge scrap preheating		Increase 33% productivity	3.2%[b]	Hasanbeigi et al. (2010)

[a] Ratio of energy savings $= \frac{E_0 - E_1}{E_0} \times 100\%$, E_0: Energy consumption before installation, E_1: Energy consumption after installation. The energy flows of iron and steel industry refers to (McBrien et al., 2016).
[b] The energy use of scrap-based EAF refers to (IEA, 2017).

process. The common way usually injects agents and oxidizing compounds into the torpedo car or hot metal transfer ladles as shown in Fig. 10 (Hasanbeigi et al., 2010).

In the secondary steel making route, steel scrap can be integrated into production processes as alternative raw material. Due to global demand for steel scrap, exportation of recycled scrap steel becomes an attractive option (Chitaka et al., 2018). Scrap pretreatment is often required to obtain high-quality scrap metal which includes routine sorting, flame cutting, and packing. In developed countries, the scrap recycling industry has been established with centralized import, processing and distribution (National Energy Conservation Center, 2012). It reveals vast potentials to reduce resource, energy consumption and waste emissions through steel scrap pretreatment.

Table 2 lists general pretreatment technologies and their improvement effect. The ratio of energy savings is used to reveal the fuel saving potentials of various pretreatments. The chemical pretreatment technologies, such as charging pre-reduced agglomerate into BF, have more significant energy savings than that of physical pretreatment technologies. It is indicated that the burden distribution has a vital role for productivity improvement.

3.2. Improved process design

With the predicted increment of crude steel production, further reduction of energy use and CO_2 emissions require more innovation beyond existing technologies (Hasanbeigi, 2013). Novel process design is developed and valued in terms of various parameters improvement and emerging energy-efficient devices.

3.2.1. Parameter control technologies

The temperature, pressure, gas flow rate and oxidizing atmosphere of combustion are all taken as the parameters that need to be controlled in the iron and steel making processes. Through optimized design of multiple parameters, it can further improve the total working performance of iron and steel industry (Feng et al., 2017).

Temperature is always required to be high to decompose the structure of iron ore and coal in current steel making (De Beer et al., 1998). Considering low-carbon and energy-efficient development, various unit operations can be performed at a lower temperature than that in present processes. Low-temperature sinter process controls oxygen concentration to facilitate the solid phase reaction, which could significantly save energy and improve performance of sinter ore (An et al., 2018). Coking process can happen at a lower temperature by heating the coke while it descends into the BF. Direct reduction process uses a synthesis gas or solid fuel directly to achieve reduction of iron oxide below the melting point (Smil, 2016). Low-temperature rolling i.e. warm-rolling or ferritic rolling is attempted to produce steels between 440 °C and 850 °C to replace the conventional grades of hot rolling and cold rolling (Ray and Haldar, 2002; Toroghinejad et al., 2003). These new steel products are conducive to energy savings, cost effectiveness and productivity.

Pressure is also controlled to reduce energy consumption in iron and steel industry. The high pressure application in coke oven is effective to control the gases emissions, thus creating large saving in process steam requirement and increased by-products yield (Hasanbeigi et al., 2010). During iron smelting process, the increased top pressure of BF is feasible to lower gas velocity and increase retention time for gas-solid reactions, which could enable a good furnace operation and energy recovery of BF (Hasanbeigi et al., 2010). A large roots-style mechanical vacuum booster pump is installed in steel vacuum degassing and vacuum oxygen decarburizing processes for better dust handling. The advances of this facility offer significant savings in energy consumption, costs reduction, speed increment, improvements in flexibility and overall productivity for steel degassing operations (Cheetham and Edwards, 2005). Table 3 lists working conditions of temperature and pressure control technologies. The common conditions of various processes are also presented.

Variable speed drive (VSD) technologies have drawn bourgeoning attentions in the last decade (Saidur et al., 2012). The steel making pumps and fans for dust and gas extraction are important loads in terms of electricity saving potential, which are excellent candidates for VSDs. By applying VSD in the iron and steel sectors, the energy saving could reach 6.3 TWh (de Almeida et al., 2003). VSD can be installed on compressors of coke oven to reduce energy consumption of COG pressurization process (Worrell et al., 2010). Also it can be equipped in the BOF and EAF processes for a better match of the fan speed with the requirements of steel making due to the frequent variation of flue gases volumes (Worrell et al., 2010). To avoid excessing air that may decrease combustion efficiency and lead to excessive waste gases, the installation of VSD on combustion air ventilators on the reheating furnace in hot rolling can help to control the oxygen level (Jones, 2012).

Ventilation control technologies e.g. air leakage reduction, oxygen enrichment and blast dewetting are indispensable for energy saving in the steel production. It is indicated that improper sealing system and damaged components in a compressed air device can cause the air leakage, which is a mainly source of waste energy in the steelworks. Improvement could be obtained by attaching a new seal between air seal bar and slide bed on the equipment side (Dhara et al., 2016). Air tight EAF technology through sealing the slag door can significantly reduce all other air entries and thermal losses in the fumes (Huber et al., 2006). In BF process, the methods

Table 3
Working conditions of temperature and pressure control technologies for steel and iron industry.

Improvement technologies	Working conditions	Common conditions	Ref.
Low-temperature sintering	1200 °C	1300 °C–1480 °C	(European Integrated Pollution Prevention and Control Bureau, 2010; An et al., 2018)
Low-temperature coking	800 °C	1100 °C	(De Beer et al., 1998; Qin and Chang, 2017)
Low-temperature iron making	900°C–1000 °C	1200 °C–2000 °C	(De Beer et al., 1998; European Integrated Pollution Prevention and Control Bureau, 2010)
Low-temperature rolling	440 °C–850 °C	500 °C–1300 °C (hot rolling)	(Toroghinejad et al., 2003; Bataille et al., 2016)
High pressure ammonia liquor aspiration system in coke oven	35–40 bar	Ammonia stripper at 1.37 bar	(Hasanbeigi et al., 2010; Qin and Chang, 2017)
High BF top pressure	>0.5 bar	0.2–0.5 bar	(Hasanbeigi et al., 2010; Geerdes et al., 2015)
Large roots-style mechanical vacuum booster pump for degassing	0.001 bar	0.00067 bar	Cheetham and Edwards (2005)

of oxygen enrichment, over-pressure, dehumidification of the blast air in the hot stoves are implemented for a higher flame temperature to achieve more effective combustion of fuels and reduce coke demands (Oda et al., 2007; Wang, C. et al., 2011).

The energy savings of above mentioned technologies are not obvious when the separated parameter control technology is applied. Thus it is necessary to develop a control system that combines all the parameters together which could meet the handling conditions to optimize the energy consumption and cost.

3.2.2. Energy-efficient devices

Energy-efficient equipment is regarded as the opportunity to reduce the energy intensity and CO_2 emissions in iron and steel industry (Jones, 2012). This section will summarize the emerging energy-efficient devices and technologies in terms of the production routes from raw material preparation to finishing process.

Considering low emissions and sintering process optimization, waste gas recovery device and energy-efficient ignition oven are developed. The sinter strand is housed to recirculate waste gases from different parts of strand and back to the sintering process (European Integrated Pollution Prevention and Control Bureau, 2010). The process could use CO content of waste gas as an energy source. Meanwhile, the recycled gas can provide most of oxygen that is required to burn the fuel. In order to save the fuel for ignition ovens, high-efficient multi-slit burner (Hasanbeigi et al., 2010) and line burner (Steel Plantech, 2016) in ignition furnace are used, which can control the duration of the flame to minimize ignition energy.

For a coke plant, there are considerable heat loss and CO_2 emissions in the conventional process of wet quenching. One alternative solution is coke dry quenching (CDQ) procedure i.e. the coke is cooled by an inert gas (Johansson and Söderström, 2011). In this way, CDQ system could collect and reuse thermal energy of the red-hot coke as steam. Other types of advanced coke oven, i.e. single chamber coking reactor and non-recovery coke oven, have been successfully installed in the coke plant (Hasanbeigi et al., 2014). A systematical coke oven technology i.e. super coke oven for productivity and environmental enhancement toward the 21st century (SCOPE21) has been demonstrated in Japan (Nomura, 2019). The technology includes three sub-processes i.e. rapid preheating of coal feeding, rapid carbonization and further heating of carbonized coke. The schematic is shown in Fig. 11.

Hot blast stove is one of the most important units in the BF iron making route (Qi et al., 2014). Conventional hot blast stoves have a number of drawbacks which can be resolved if the combustion chamber is eliminated, i.e. to develop a top combustion hot blast stove known as "shaftless hot stove". The top combustion hot stove can provide complete gas combustion without pulsation, which could achieve the high efficient combustion even in the operation only with flue gas (Japanese Smart Energy Products and Technologies, 2019b). A novel Kalugin shaftless stove with a smaller diameter pre-chamber at the top of the dome has become a future top combustion hot stove. With regard to further reduce CO_2 emission of iron making, many options are proposed, e.g. Corex, Finex, Tecnored, Itnk3 process, Paired straight hearth furnace, Coal-based HYL process, Coal-based MIDREX® process. (Oda et al., 2007). These technologies have been reviewed and compared by Hasanbeigi et al. (2014), which are considered as the promising alternatives of traditional iron making process.

One of the major innovations in BOF steel making lies in the injection system of converter furnace. Top blown BOFs have been converted to combined blowing process with an additional bottom agitation (Choudhary and Ajmani, 2006). A small amount of inert gas will be injected to BOF from the bottom of the convertor, which is mixed with oxygen injected from top of furnace. Inert gas injection is beneficial to reduce the flux and oxygen consumption. Energy savings in EAF depend largely on the highly efficient arc furnace. The furnaces such as direct current (DC) arc furnace and Comelt furnace operate on a DC basis. DC can generate the heat which is used to melt and stir the steel after charging scrap into the arc furnace (New Energy and Industrial Techonology Development Organization, 2008). Various arc furnaces for preheating the scrap, i.e. Contiarc furnace, post combustion shaft furnace, ecological and economical high-efficient arc furnaces (ECOARC™) have been developed and put into practice. It is demonstrated that using waste heat to preheat the scrap can reduce the power consumption of EAFs. Furthermore, new transformers and electric systems have been installed on EAF operators to enhance the power of the furnaces (Jones, 2012).

Technologies in casting, rolling, and finishing processes may dramatically reduce energy consumption. These efficient opportunities refer to innovation heating furnaces, e.g. Rapidfire™ edge heater (Department of Energy, 2000), flameless oxyfuel combustion furnace (Narayanan et al., 2006), walking beam furnace, and

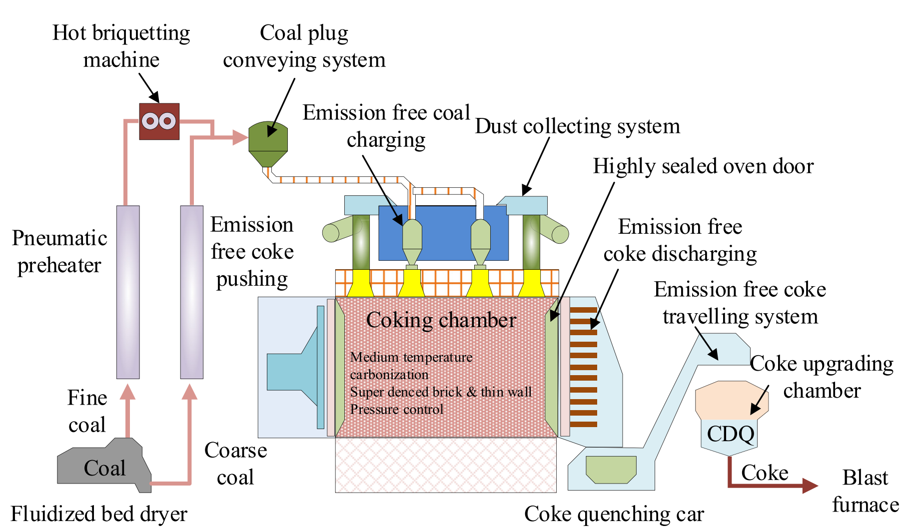


Fig. 11. Schematic diagram of SCOPE21 process flow (Hasanbeigi et al., 2010).

Table 4
List of energy-efficient devices for iron and steel industry.

Process	Technologies	Improvement effect	Investment cost	Limitation	Ref.
Sinter	Partial recycling of waste gas from the whole strand	Reduce coke breeze consumption by 10–15%	\$ 18.6 million[a]	Operational flexibility of the strand	European Integrated Pollution Prevention and Control Bureau (2010)
	Multi-slit burner in ignition furnace	Reduce ignition energy by 30%	–	–	Hasanbeigi et al. (2010)
Coking	CDQ	Generate 0.5–0.7 t steam·t^{-1} coke and 0.504–0.67 electricity·t^{-1} coke	\$ 99.3 t^{-1} coke	Coke blowing up and carrying-over phenomenon	(Jones, 2012; Steel Plantech, 2015a)
	Single chamber system coking reactor	Improve thermal efficiency from 38% to 70%	–	Mostly considering for new plants	Jones (2012)
	Non-recovery coke ovens	Produce 2.3–2.5 GJ electrical power·t^{-1}coke	\$ 365 million[b]	Emission requirements and demand of steam quality	(European Integrated Pollution Prevention and Control Bureau, 2010; Hasanbeigi et al., 2010)
	SCOPE21	Reduce 21% energy consumption	Reduce 18% and 16% production and construction cost	–	Hasanbeigi et al. (2010)
BF	Top combustion hot blast stove	Save energy in the hot stove by 1–2% (5000 m^3 BF)	–	Impossible to replace the existing stove/difficult to control gas-air ratio	Japanese Smart Energy Products & Technologies (2019b)
	Kalugin shaftless hot stove	Increase thermal efficiency by 8–12%	\$ 9.58 million (2500 m^3 BF)	–	He and Wang (2017)
BOF	BOF bottom stirring	Reduce flux quantities by more than 10%	–	Difficult to maintain the continuation of effective stirring	Choudhary and Ajmani (2006)
EAF	DC arc furnace	Save 0.036–0.32 GJ·t^{-1} steel	\$ 22.13 million[c]	–	New Energy and Industrial Techonology Development Organization (2008)
	Comelt furnace	Save 0.36 GJ·t^{-1} steel	Reduce maintenance costs	–	Worrell et al. (2010)
	Contiarc furnace	Reduce energy losses by 0.792 GJ·t^{-1} steel	–	–	Jones (2012)
	Post-combustion shaft furnace	Reduce 0.28–0.4 GJ electric power·t^{-1} liquid steel	Customized operating cost	–	(SMS group; Jones, 2012)
	ECOARC™	Save 0.36 GJ·t^{-1} steel	More initial costs in a short term	–	Steel Plantech (2016)
	ECOARC light™	Save 0.252–0.288 GJ·t^{-1} steel	Lower initial cost	–	Steel Plantech (2016)
	Ultra-high power transformers	Save 0.061 GJ·t^{-1} steel	\$ 3.9 t^{-1} steel	Installation sites	Jones (2012)
	Eccentric bottom tapping	Save 0.054 GJ·t^{-1} steel	\$ 4.5 t^{-1} steel[d]	Limited by the size, type and life of the existing one	Jones (2012)
Casting/Rolling/ Finishing	Rapidfire™ edge heater	Save energy by 28%	Lower installation cost	–	Department of Energy (2000)
	Flameless oxyfuel combustion	Increase 50% heating capacity and decrease 40% fuel consumption	Depend on the cost of oxygen	High CO_2 concentrations during oxy-fuel coal combustion	Narayanan et al. (2006)
	Walking beam furnace	Reduce 25% electricity and 37.5 fuel consumption	Lower operation cost	Mostly by means of natural gas	Jones (2012)
	Regenerative burner	Save 800–1000 crude oil equivalent·$year^{-1}$	Lower maintenance cost for ladle refractory	–	New Energy and Industrial Techonology Development Organization (2008)
	Continuous casting machine	Reduce 0.072–0.108 GJ power·t^{-1} steel	\$ 99.29 t^{-1} steel	Solidification control	(New Energy and Industrial Techonology Development Organization, 2008; Nayak, 2014)
	Castrip® process	Save energy by 80–90% over conventional methods	Lower capital cost	High heat flux	Sosinsky et al. (2008)
	Endless strip production	Reduce energy by 45%	Lower investment and processing cost	–	Arvedi et al. (2008)

(*continued on next page*)

Table 4 (*continued*)

Process	Technologies	Improvement effect	Investment cost	Limitation	Ref.
	Continuous annealing line	Reduce fuel consumption by 33%	\$ 225 million[e]	High installation costs	(Worrell et al., 2010; Steel Plantech, 2016)

[a] The investment of a total waste gas flow of 1.2 million $Nm^3 \cdot h^{-1}$ from three sinter strands was EUR 17 million in Netherlands. The cost was converted to USD according to current exchange rate in April 2020.
[b] The investment includes the coke oven facilities, coal handing and the power plant for a 1.2 million t coke·$year^{-1}$ greenfield heat recovery plant in 1998, US.
[c] The investment includes equipment cost JPY 2000 million and construction cost JPY 400 million. The cost was converted to USD according to current exchange rate in April 2020.
[d] The investment only includes modification cost which is for a Canadian plant with an annual production capacity of 760000 t.
[e] The investment is for a continuous annealing facility with a capacity of about 5000000 t $year^{-1}$ in US.

regenerative burner, which can provide more furnace heating capacity and lower fuel consumption. Casting, rolling and finish processes need to meet various demands, thus it is necessary to provide solutions by supplying linking lines e.g. a continuous casting machine that produces slabs, blooms and billets by pouring molten steel into a mold (New Energy and Industrial Techonology Development Organization, 2008). Other integrated technologies are adopted in iron and steel industry e.g. endless strip production that combines casting and rolling into a continuous process (Arvedi et al., 2008), and continuous annealing lines that integrate cleaning, heating, cooling, temper rolling and refining in a single line (Liu et al., 2015; Steel Plantech, 2016).

Table 4 summarizes general energy-efficient devices, technologies and their characteristics according to the iron and steel production routes. The emerging technologies generally have the higher investment cost and difficulties to replace the existing construction. But they are still the attractive opportunities to reduce emissions and energy consumption for iron and steel industry in the future.

3.3. *Outgoing flow utilization*

The useful outputs from global steel production can be recycled during the making process or sold for use by other industries. The main by-products generated from iron and steel production are slags (90% by mass), dusts, sludge and by-product gas (World Steel Association, 2018). Molten slag and process gas are all exhausted at different temperatures which carry a great deal of waste heat. Considering local and global steel production, by-products as value-added products or extra energy output, become environmental concerns and cost-saving opportunities in industrial applications (Oge et al., 2019). This section mainly focuses on the direct utilization of by-products and wastes. Waste heat utilization from slag and by-product gas will be separately illustrated in section 4.1.

3.3.1. *Utilization of slag and dust*

Slag in steel industry can be classified into BF slag and steel making slag (Li, 2017). BF slag has been categorized into three main types by the cooling ways, i.e. air-cooled, granulated, and pelletized (or expanded). BF slag can be safely used as the raw material in the cement industry due to the low iron content. Steel making slag uses similar cooling method as air-cooled BF slag which could be reused in soil conditioners and fertilizers.

In the iron and steel metallurgical processes, dust and sludge are collected in the aspirating equipment. Before BFG is recovered by a TRT generator, a dry-process dust collector will be used for cleansing BFG. Two typical dry-process dust collectors have been used to avoid large temperature and pressure loss of the gas that passes through the dust collector, bag-filter collectors and electrostatic precipitators (Japanese Smart Energy Products and Technologies, 2019a). Since BF dust generally contains high level

Table 5
List of slag and dust recycling technologies for iron and steel industry.

Source	Characteristics	Recycling technologies	Ref.
BF air-cooled slag	Hard and dense	Make construction aggregate; Used in concrete-based products, road, clinker raw material, railroad ballast, roofing, mineral wool and soil conditioner	World Steel Association (2018)
BF granulated slag	Sand-sized particles of glass	Make cementitious material	Liu et al. (2019)
	Crystalline and amorphous BF slag	Used as an adsorbent of phosphate from water solutions	Kostura et al. (2005)
BF pelletized slag	Vesicular texture	Make lightweight aggregate	World Steel Association (2018)
BF flue dust and sludge	High level of iron oxides and coke fines	Produce sinter	Singh et al. (2014)
	High carbon content of the sludge	As an adsorbent for Cu^{2+} from aqueous solutions; As a reducing agent to remove zinc from the steel making dusts.	(Das et al., 2007; Omran and Fabritius, 2019)
BOF slag	High density and a high crushing strength	Produce concrete	Fisher and Barron (2019)
	The content of calcium and magnesium silicates	CO_2 sequestration	Fisher and Barron (2019)
	The phosphorus content of slag	As fertilisers for crops	Annunziata Branca et al. (2014)
	Hard characteristics	Used as the base and sub-base layer of road	Das et al. (2007)
	High porosity and large surface area	Marine applications	(Yi et al., 2012; Fisher and Barron, 2019)
BOF dust and sludge	Very high iron and appreciable amount of CaO content	Recycled to iron and steel industry; Land filled, road bed and cement production.	Das et al. (2007)

Table 6
The properties of by-product gas in iron and steel industry (Wang et al., 2008; Uribe-Soto et al., 2017).

Type	Source	Chemical composition	Heat value ($kJ \cdot m^{-3}$)	Production/t product
COG	Coke oven battery	H_2: 45–64%; CH_4: 20–30%; CO: 5–10%; CO_2: 2–5%; O_2: 0.1–4%.	16000–19300	400–450 m^3 t^{-1} coke
BFG	BF	H_2: 4%; CO: 25%; CO_2: 20%; N_2:41%.	3000–3800	1400–1800 m^3 t^{-1} iron
LDG	Converter	CO_2: 15–20%; O_2: ≤2.0%; CO: 60–70%; N_2: 10–20%; $H_2 \leq 1.5\%$.	7500–8000	80–100 m^3 t^{-1} liquid steel

of carbon and iron, it can be recycled through sinter making process. The effectiveness of BF sludge has been investigated as an adsorbent to purify contaminated solutions. Steel making sludge needs to be optimally dried and become operable before recycling. The agglomeration of steel making sludge could be the ideal approach to maximize its use in sinter feed (Das et al., 2007).

Table 5 lists specific characteristics and general recycling technologies of slag, dust and sludge in iron and steel industry. Utilization of solid by-products can prevent them from being transported to landfill, thus saving energy and natural resources as well as significantly reducing CO_2 emissions (World Steel Association, 2018).

3.3.2. By-product gas recovery and conversion

Three main by-product gases i.e. COG, BFG and LDG are generated in the processes from coal to steel. The concerning component, heat valve and quantity of by-product gas are indicated in Table 6. In general, these streams contain similar compound with different proportions (Uribe-Soto et al., 2017). As the first generated gas, COG is produced from dry distillation of coking coals in the absence of oxygen. It could be not only used as a heating source but also mixed with BFG for power generation. Besides, COG can potentially generate a high value added products by reacting with CO_2 and CO (Li et al., 2018). BFG serves as a by-product of BF in the furnace process. It is used to blend with other gases e.g. natural gas for combustion to generate the power, which could be combined with steam cycles for a higher efficiency of 42% in steel mill applications. Besides, it could increase furnace temperature through combustion (Chen et al., 2011). LDG is created from pig iron during the steel making process. LDG recovery is the most energy-saving technology in the BOF process (Worrell et al., 2010). By-product gases have a close relationship with reduction of primary energy while it is quite significant for thermal utilization. The above two applications will be discussed in different following subsections. This part mainly focuses on recovering by-product gases for valuable compound and producing a high value-added product.

Considering valuable compound recovery, H_2, CH_4 and CO are the primary candidates. Due to their different proportions in off-

Table 7
Selected research works for off-gas recovery and thermochemical by-product gases.

Gas	Use	Experiment/Simulation	Remarks	Ref.
COG	H_2 recovery	Thermal analysis& experiment	Layered beds are filled with zeolite 5A for a seven-step two-bed PSA process for producing H_2	Yang and Lee (1998)
COG	H_2 recovery	Thermal analysis& experiment	H_2 separation process is segmented into four sections in terms of the saturated temperature and content of the components in COG	Chang et al. (2008)
COG	H_2 and CH_4 recovery	Experiment	A prism membrane is used to purify COG; H_2 and CH_4 have the purity higher than 90% and 60%	Shen et al. (2007)
BFG	CO_2 and CO recovery	Experiment	A bench scale PSA plant is constructed; 6.3 t CO_2 is recovered with a 225 s cycle time and 33% CO_2 concentration of raw gas	Saima et al. (2013)
LDG	CO recovery	Experiment	A first CO-PSA commercial plant was constructed in 1989; The product CO capacity of plant is 150 $Nm^3 \cdot h^{-1}$	Kasuya and Tsuji (1991)
BFG	CO_2 separation	Economic analysis	The polymeric gas separation membrane is used to separate CO_2; Cost is from $ 25–36 t^{-1} CO_2[a]	Ramírez-Santos et al. (2017)
BFG&LDG	CO_2 separation	Experiment	CO_2 is recovered by absorption in a Selexol® process	Gielen (2003)
COG	H_2 production by reforming	Simulation	The sorption-enhance steam reforming can obtain higher amount and purity of H_2 than those in the common steam reforming	Xie et al. (2017)
COG	Syngas production	Experiment	The H_2-rich COG is converted to syngas via the partial oxidation and CO_2 reforming at a high space velocity and lower temperature	Guo et al. (2008)
COG	Methanol production	Experiment	The production capability of COG has reached 2.06 million tons	Xie et al. (2010)
COG&LDG	Methanol production	Thermal analysis& experiment	The stored heat from the intermittently emitted LDG is supplied to COG; Methanol is finally produced from the obtained gas	Maruoka and Akiyama (2006)
COG&LDG	Methanol production	Techno-economic analysis	Using excess COG and 40% of the available LDG to produce methanol shows efficient gas utilization	Lundgren et al. (2013)
BFG&COG	Higher alcohol production	Environmental and economic evaluation	Using BFG&COG, higher alcohols are produced and annual CO_2 emissions reduction is 14820 t	Guo et al. (2013)
COG	COG methanation	Experiment	Toluene could be completely converted into CH_4, CO and CO_2 over bimetallic catalysts	Cheng et al. (2011)

[a] The cost for a two stage membrane process which recoveries CO_2 up to 99% and keeps inert N_2 below 5% is EUR 23–33 t^{-1} CO_2. It was converted to USD according to current exchange rate in April 2020..

gas, it may cause different recovery levels. H_2 and CH_4 are easier to be recovered from COG, and CO is usually recovered from BFG. The main recovery technologies could be pressure swing adsorption (PSA) and membrane separation process (MSP). Cryogenic separation is also suitable to be applied if gas proportion and external conditions are satisfied. It is demonstrated that 90% of H_2 could be recovered by using PSA with a purity up to 99.99%. Comparably, 80–98% of H_2 could be recovered with a purity of 90–99%. By using PSA or MSP, the quality of CH_4 concentrated stream may be improved. Only PSA and chemical absorption systems are suitable to separate CO from BFG due to high proportion of N_2 (Uribe-Soto et al., 2017). These two systems are also applicable for separating CO_2 from BFG and LDG. Activated MDEA (methyldiethanolamine) is a common solvent for CO_2 absorption (Gielen, 2003). Another possibility for CO_2 capture is to convert CO contained in BFG and LDG into CO_2 for concentrating the stream (Ho et al., 2011). This process can be accomplished by using water gas shift reaction under high temperature and pressure. The absorption solvent will be used to separate CO_2 generated from shift reaction (Gielen, 2003).

COG is highly rated as a feedstock to obtain the value-added products due to its high content of organic compound. Syngas production from COG is mainly composed of steam reforming, dry reforming and partial oxidation processes (Razzaq et al., 2013). The steam reforming of CH_4 is currently the main technology for syngas production. The CO_2 (dry) reforming is regarded as the alternative processes to steam reforming, which has been widely proposed. The partial oxidation of CH_4 is a mildly exothermic reaction, which is more cost-efficient. H_2/CO ratio of syngas from the partial oxidation is between that of syngas obtained from steam and dry reforming. It is possible to synthesize methanol with the use of COG-derived syngas when it is produced from dry reforming at a H_2/CO ratio close to 2 (Bermúdez et al., 2010). COG with rich H_2 contents is considered to be ideal for a sustainable methanol production as it can meet the criteria of resource utilization and environmental protection (Xie et al., 2010; Razzaq et al., 2013). Half of CO_2 produced upon methanol consumption will be recycled in the dry reforming process (Bermúdez et al., 2013). Synthetic natural gas could be produced through a co-methanation reaction of CO and CO_2 (CO_x) in COG for CH_4 enrichment by using appropriate catalysts (Razzaq et al., 2013). Ni-based catalysts have been widely employed for methanation reaction because of their high selectivity for CH_4 and low cost (Zhao et al., 2012). $Ni/MgO/Al_2O_3$ catalysts exhibit excellent activity, stability and resistance to carbon deposition for the catalytic conversion of tar in H_2-rich hot COG (Yang et al., 2010).

Table 7 summarizes the selected research studies for off-gas recovery and thermochemical by-product gases in terms of simulation, experiment and techno-economic analysis.

4. Efficient technologies for secondary energy

It is obvious that the secondary energy is considered to be utilized after primary energy is explored as much as possible. This is mainly because the mass network optimization in primary energy is mainly based on the single process and flow improvements. Secondary energy resources i.e. by-product gas and waste heat are considerable which are produced during the steel making processes. Thus the recovery technologies should also be valued when compared with those used for primary energy savings. These resources could be converted into steam or other forms such as power, heating and cooling output to meet the concerning requirements in the iron and steel works. In addition to thermal energy, by-products have chemical energy that can be recovered as fuel via combustion or high pressure gas outputs (McBrien et al., 2016).

Table 8
Selected researches for molten slag sensible heat recovery technologies.

Slag	Heat recovery technologies	Research/Demonstration	Remarks	Ref.
Physical method				
BF slag	Mechanical impingement	Not for a long-term commercial use	Generate 250 °C saturated steam and 65% heat recovery rate	Mizuochi et al. (2002)
BF slag	Stirring crushing	Experiment	Recover 59% of slag energy	Web (2014)
BF slag	Rotating drum process	Experiment	Heat recovery rate of 40–60%	Zhang et al. (2013)
BOF slag	Air blast method	Demonstration	Recover 41% and 39% of heat by the steam and hot air	Barati et al. (2011)
BF slag	Air blast by rotating cup atomizer	Demonstration	Recover 59% of the slag heat	Barati et al. (2011)
BF & BOF slag	Spinning granulating	Demonstration	Obtain hot air at a temperature of above 600 °C	Barati et al. (2011)
Chemical method				
BF slag	Drive thermoelectric power generation device	Simulation	Produce 0.00093 MW electrical energy and achieve 2% conversion efficiency	Meng et al. (2014)
BF slag	Produce H_2-rich gas by wet sludge gasification	Experiment	Heat recovery rate of 64.35%	Luo et al. (2019)
BF slag	Produce H_2-rich gas by catalytic pyrolysis of biomass	Experiment	Achieve complete pyrolysis of biomass	Luo et al. (2017)
BF slag	Produce syngas by bio-oil dry reforming	Experiment	The conversion of optimal bio-oil can reach 90.15%	Yao et al. (2018)
BF & BOF slag	Biomass gasification	Experiment	Recover 1.1 MJ heat from the slags$\cdot$kg^{-1} biomass	Sun et al. (2019)
BF slag	Steam gasification of coal	Kinetic analysis	BF slag accelerates the gasification rate	Duan et al. (2016)
BF slag	Pyrolysis of printed circuit boards	Experiment	The boards are effectively pyrolyzed with a slag/board ratio of 5:1	Qin et al. (2013)
BF & BOF slag	Convert hot slag into qualified raw materials in cement, concrete and road pavement	Demonstration	The upper limit proportion for the amount of modifiers is about 19–25 wt%	Li and Dai (2018)
BF & BOF slag	Convert hot slag into glass ceramics, mineral wool and potassium silicate fertiliser	Demonstration	The energy save rate is up to 80%	Li and Dai (2018)

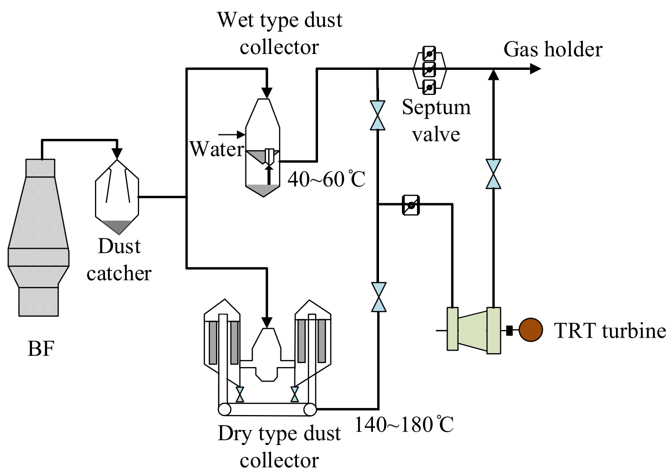


Fig. 12. The schematic flow diagram of wet and dry TRT systems (New Energy and Industrial Techonology Development Organization, 2008).

4.1. Utilization of by-product for waste heat recovery

Compared with the utilization and conversion of by-product in section 3.3, this section mainly focuses on recovering by-products in terms of heating and power generation. The recovery technologies are possible in three different forms: recovery as hot air or from steam, conversion of waste heat through chemical reaction, and the use of thermoelectric power generation (Jouhara et al., 2018).

4.1.1. Slag thermal utilization

BF slag in iron-making process is exhausted at the high temperature of 1450–1650 °C (Li, 2017). Steel making slag is formed in a molten or red-hot state at a temperature of 1300–1700 °C (Horii et al., 2013). Therefore, a great deal of high-grade heat is carried with the slag which accounts for 10% of waste energy and 35% of high-temperature waste heat in steel industry. Compared with utilization of slag in subsection 3.3.1, high-temperature waste heat recovery technologies of slag are vital to achieve energy saving and emission reduction in the iron and steel industry. Current heat recovery technologies can be generally classified into physical and chemical methods. Physical methods have been widely investigated, for example mechanical crushing, air blast and centrifugal granulating process. With respect to chemical methods, CH_4 reforming reaction and coal gasification process take the leading roles. These waste heat recovery and utilization technologies have been partially reviewed (Zhang et al., 2013). Table 8 lists selected researches for molten slag sensible heat recovery under different methods.

4.1.2. By-product gas for thermal utilization

As mentioned above, by-product gas is a main part of secondary energy resources, which accounts for 30–40% of total energy consumption of iron and steel industry. In addition to direct utilization of by-product gases illustrated in subsection 3.3.2, the gases can be served as a fuel by means of their thermal and chemical energy. For thermal use, the gases are burned for heating different furnaces, steel before rolling, slabs or fed to a thermal power plant. It is indicated that most steel mills in Europe have developed thermal integration projects and Chinese steel mills start to convert COG into liquefied gas.

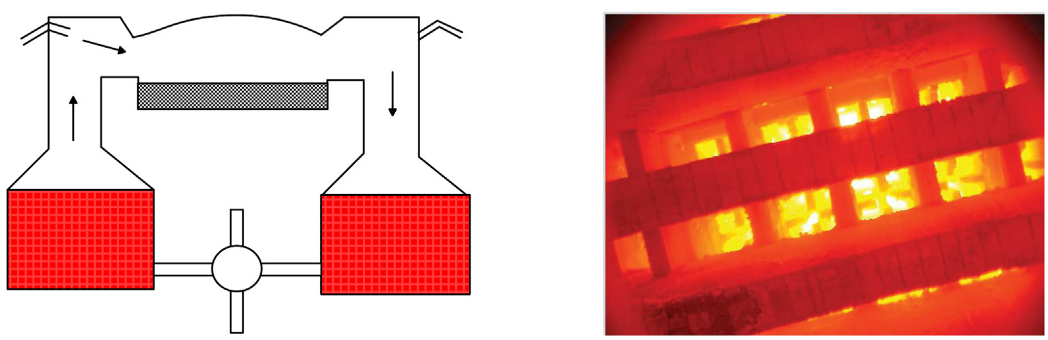
CDQ recovers the sensible heat of red-hot coke using inactive gas in a dry process. After the coke is cooled to approximately 200 °C, the circulating gas has been heated to 800 °C or higher which could generate high temperature and pressure steam in the boiler. The steam is used as process medium or driving force for power generation (Japan Coal Energy Center, 2007). During iron smelting process, BFG has a pressure of 0.2–0.236 MPa and temperature of approximately 200 °C at the top of furnace. Equipping TRT unit is the best way to recover the thermal energy of BFG (Wu and Yang, 2012). Energy is recovered by means of an expansion turbine which is installed after the top gas cleaning device (European Integrated Pollution Prevention and Control Bureau, 2010). TRT systems are categorized as wet and dry systems, depending on the method that they use to remove the dust particles. A typical modern TRT of the dry type generates 0.055 $MWh \cdot t^{-1}$ of pig iron under the condition of high-pressure operation of the BF, whereas a wet-type TRT generates 0.03 $MWh \cdot t^{-1}$ of pig iron (Oda et al., 2007). The schematic flow diagram of wet and dry TRT processes is shown in Fig. 12. Other case studies using by-product gases for thermal use in iron and steel industry are selected in Table 9.

Table 9
Selected cases for thermal utilization of by-product gases.

Gas type	Use	Steel company/Location	Remarks	Ref.
BFG&COG	Power generation	ArcelorMittal Tubarão/Brazil	Three power plants are based on Rankine regenerative cycle; Plant 1 and 2 generate 132 MW whereas Plant 3 produces 69 MW	Modesto and Nebra (2009)
BFG&COG	Power generation	-/China	On-site test of using the recovered waste fuel gas to power the boiler; A high stability could be achieved	Hou et al. (2011)
BFG&COG	Power generation	Alchevsk Coke Plant/Ukraine	Use 9 MW turbine generator to generate a net annual power of 54 × 10^3 MWh	NEFCO (2010)
BFG&COG	Heating and power generation	Sandvik AB (scrap-based steel plant/Sweden	Gases are to drive combined heat and power (CHP) plant for power generation and district heating; TRT technology is used to generate electricity with 0.04–0.06 MWh electricity$\cdot t^{-1}$ of iron	Johansson and Söderström (2011)
COG	Power generation	Profusa/Spain	Plant power output could reach 8.95 MW	Schneider (2011)
COG	Heating and power generation	Shandong Jinneng Coal Gasification Co., Ltd./China	Power output is around 0.0016 $MWh \cdot m^{-3}$ with 3.09 kg simultaneous steam production	Razzaq et al. (2013)
LDG	Power generation	Aceralia/Spain	Plant power output could reach 0.0121 MW	Schneider (2011)
LDG&COG	Heating and power generation	-/Spain	When the energy is produced only with LDG&COG, 169.42 $Nm^3 \cdot MWh$ of natural gas are saved	García et al. (2019)

Table 10
Heat outputs and energy directly produced from per ton of steel product (Department of Energy, 2008; Li et al., 2010; McBrien et al., 2016).

Process	Output	Temp. (°C)	Thermal energy (GJ·t^{-1})	Other energy (GJ·t^{-1})
Sintering	Sinter	700–800	0.88–0.94	–
	Sinter flue gas	300	0.69	–
	Stack exhaust	350	0.34	–
Coking	Coke	1000–1100	0.55–0.59	–
	COG	649–982	0.17–0.18	0.69
	Flue gas	250	0.10	–
Iron making	BFG	180–500	0.32–0.82	4.12
	Blast stove exhaust	250	0.06	–
	BF slag	1450–1500	0.49	–
	Cooling water from BF	40	0.95	–
Steel making (BOF)	LDG	1600–1800	0.18–0.21	0.13
	BOF slag	1500–1700	0.02–0.05	–
Steel making (EAF)	Exhaust gases with recovery	204	0.97–1.93	–
Casting	Steel	1200–1600	0.7–1.39	
	Steel latent heat	1200	0.27	–
Hot rolling	Reheat exhaust	700	0.20	–
	Hot rolled steel	900	0.53	–



(a) (b)

Fig. 13. A typical diagram of regenerative furnace (a) schematic, (b) photo (Department of Energy, 2008).

4.2. Waste heat recovery technology

Waste heat is another important secondary energy resource in the iron and steel industry. However, only a small part of waste heat is currently recovered, which reveals the great potentials for further utilization. Waste heat could be categorized by dividing temperature range into low, medium, and high-quality sources, and the range could be different when considering different classification criteria. Temperature of high quality source is generally higher than 500 °C which includes high temperature COG, LDG, electric furnace gas and heating furnace flue gas; high temperature liquid includes iron slag, steel slag and high temperature water; high temperature solid waste heat e.g. high temperature sintering materials, high temperature coke and high temperature steel. Temperature of medium quality heat source usually ranges from 150 °C to 500 °C, including BFG and sintering flue gas. Low quality of heat source is commonly lower than 150 °C, including waste steam, hot water, all kinds of low temperature flue gas and low temperature materials (Ma et al., 2012). These sources of waste heat output are illustrated in Table 10.

Methods to recover waste heat mainly consist of heat transfer between gases and liquids, preheating the furnaces, generating mechanical and electrical power. The high-quality heat source could be transferred to medium and low temperature process. All these should observe general guidelines of waste heat utilization as follows: (1) Heat is used directly in the process with less heat transfer. For instance, sensible heat of the product is directly transported to the next process. (2) After heat conversion by using heat exchanger, power generation or CHP are considered for further utilization, e.g. flue gas produces steam for power generation based on TRT and CDQ. Waste heat recovery potentials in the iron and steel industry mainly focus on the range of medium-high temperature. Challenges and limitations are related to recover methods due to the presence of dirty and low quality waste heat (Jouhara et al., 2018).

4.2.1. Heating

For the methods to recover waste heat in the iron and steel industry, it is recognized that heat exchanger is the most investigated. Recuperators, regenerators, and heat pipe are used for preheating and reheating (Ma et al., 2017). Recuperator has a variety of types, which are determined by heat transfer methods in terms of simple radiation, convective, tube type, combined radiation and convection type. It usually exchanges high temperature heat which comes from either metallic or ceramic materials. Regenerators are more frequently used for coke ovens, which are adopted to preheat the hot blast and blast stoves used in iron making. Regenerative furnaces are composed of two grid chambers and each contains refractory material i.e. the checker. In one chamber the combustion gases pass through the checker and enters the furnace in the other chamber, and the checker is heated, or regenerated with the outgoing hot exhaust gas. The furnace operates alternatively, and the flow is reversed so that the new combustion air can be heated by the checker. A typical diagram of regenerative furnaces is shown in

Table 11
Selected studies of heat to heat technologies for steel and iron industry.

Process	Waste heat recover method	Technologies	Remarks	Ref.
Sintering	Recover the sinter cooler's exhaust gas as steam, and reuse of exhaust heat as thermal source of sinter production	Recirculation	The system allows up to about 60% of exhaust heat from the sinter cooler to be reused as steam or electricity	Steel Plantech (2015b)
Coking	Preheat the coke oven using the remaining recycled gas	Regenerator	Regenerators are suitable for high temperature applications with dirty exhausts	Jouhara et al. (2018)
	Extract hot gas from the oven flue gas to provide a heat source	Radial heat pipe	The system can produce saturated steam 0.19 t^{-1} coke	Zhang et al. (2015)
	CDQ to generate steam	Waste heat boiler	For a plant with 450000 t $year^{-1}$ coke capacity, 450×10^3 MWh·$year^{-1}$ steam can be produced	(New Energy and Industrial Techonology Development Organization, 2008; Jones, 2012)
Iron making	Recover waste heat from the combustion exhausts for reheating the BF and preheating the combustion air	Regenerator	The typical operating temperature of reheating furnaces (1350 °C) is achieved without natural gas enrichment	(Cuervo-Piñera et al., 2017; Jouhara et al., 2018)
	Hot stove waste heat recovery device	Rotary, plate and heat pipe	The recovery rate of hot stove flue gas sensible heat ranges from 40 to 50%	New Energy and Industrial Techonology Development Organization (2008)
Steel making	Recover waste heat from the furnace gas duct	Waste heat boiler	0.19 GJ·t^{-1} energy can be saved when implementing heat recovery method	McBrien et al. (2016)
	Recover waste heat in a slag cooling process	Heat pipe	As waste water mass flow rate varies between 0.8 and 1.9 m^3 h^{-1}, effectiveness of the exchanger ranges from 0.085–0.192	Ma et al. (2017)
Rolling	Recover waste heat in a steel wires cooling process	Flat heat pipe	Heat recovery rate during laboratory test is 0.005 MW and in the industrial test is 0.01 MW	Jouhara et al. (2017)

Table 12
Heat to power cycles for waste heat recovery (Department of Energy, 2008).

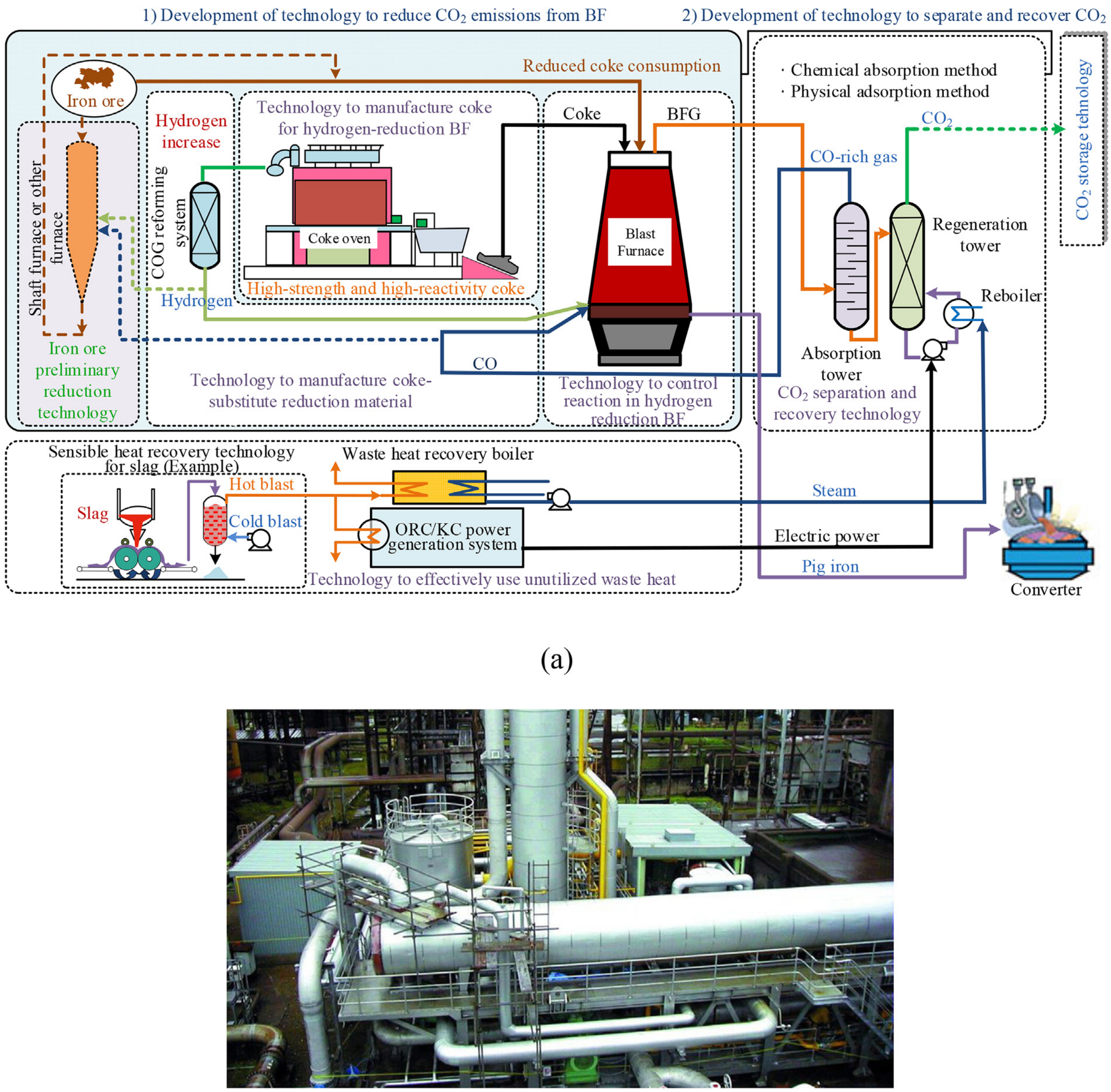
Cycle	Heat source	Temperature	Thermal efficiency	Capital cost
Rankine cycle	Exhaust from furnaces.	340–550 °C	28%–42%	\$ 1.1–1.4 MW^{-1}
KC	Exhaust from furnaces or boiler.	100–400 °C	19%–38%	\$ 1.1–1.5 MW^{-1}
ORC	Gas and boiler exhaust, heated water	70–300 °C	4%–10%	\$ 1.5–3.5 MW^{-1}
Thermoelectric Generation	Not yet demonstrated in industries	150–1000 °C	2–10%	\$ 20–300 MW^{-1}
Thermophotovoltaic systems	Exhausts from continuous casting	1000–1500 °C	2–7%	\$ 0.4–3.400 MW^{-1}

Fig. 13.

As a common heat exchanger in steel mill, waste heat boiler is suitable to recover heat from medium to high temperature exhaust gases and is used to generate steam as an output which can be used for power generation or back to the system for energy recovery. It mainly consists of water tubes that are placed in parallel to each other and in the direction of the heat leaving the system (Jouhara et al., 2018). An auxiliary burner is usually needed if the waste heat is not sufficient to produce the required amount of steam (Doty and Turner, 2004). Sensible heat of coke can be captured by CDQ in which hot coke is quenched by inert gases and the recovered thermal energy is used to generate steam in a downstream boiler (Sun et al., 2015). When the BOF uses the open combustion system, a waste heat boiler is always required to recover waste heat which results from the reaction of oxygen in the furnace gas duct (Jouhara et al., 2018).

Another heat recovery device is the gas to gas passive air preheater for low to medium temperature, which could be generally divided into plate type and heat pipe. Plate type is quite common which has different parallel plates for hot and cold gas flow (Abou Elmaaty et al., 2017). Considering heat pipe type, working fluids are operated between hot and cold ends of each pipe which has a capillary wick structure (Zheng et al., 2018). Ma et al. (2017) designed and established a waste heat recovery experimental system by using a heat pipe heat exchanger for recovering the heat in a slag cooling process. It is indicated that heat transfer performance is improved by using online cleaning device. Thermal resistance of outer surface is reduced by removing the dirt.

Heat pump is thermodynamically originated from an inversed Carnot cycle, which happens in the opposite direction of spontaneous heat transfer. Based on this thermal cycle, it is defined as a device that could absorb heat from a relatively cold source and release it to a hot source by consuming a small amount of external power (Zhang et al., 2016). Heat pump systems show great potentials to extract heat from various heat sources. For instance, cooling water in the iron and steel industry which could be used for the antifreeze of coke, crush and sieving system, and district heating of office and operating rooms. It is worth noting that the upgraded



(a)

(b)

Fig. 14. Case of KC demonstration with steel industry (a) schematic, (b) photo (Global Geothermal Advanced Waste Heat Engineering).

heat should be reused in industrial processes of steel work. It is meaningless to upgrade the heat source for power generation or other energy conversion systems by using heat pump systems though energy efficiency will be improved slightly. Table 11 summarizes selective case studies of heat to heat technologies in steel and iron industry.

4.2.2. Power generation

For low grade heat recovery, power generation technologies are still considered to be the major energy conversion methods if no heating, cooling or other demands are required to be satisfied. Thermal driven power technologies have various thermal cycles in terms of different heat source temperatures. Rankine cycle is a typical thermodynamic cycle which converts waste heat to mechanical power. The suitable temperature for steam Rankine cycle is better to be higher than 340 °C. Otherwise, the cycle becomes less efficient due to low pressure steam (Wang, T. et al., 2011). Performance of ORC and KC are better than that of Rankine cycle when using low temperature heat source. Similar with Rankine cycle, organic working fluids with low boiling point temperatures are adopted to utilize the lower temperature heat source such as industrial waste heat and solar heat. Low temperature heat is transferred into useful work output (Shi et al., 2018). The most appropriate temperature range for ORC depends on the selected refrigerant, which will have an influence on thermal efficiency. Nonetheless, the main disadvantage of Rankine type cycle is that the endothermic evaporation process keeps constantly boiling which could not well match the trend of heat source. Due to the large temperature difference, energy efficiency cannot be further improved. Comparably, KC was invented in the 1980s. It has a variable temperature gradient in the evaporating process by using binary mixture of ammonia and water, which could bring about a

Table 13
The demonstration studies of KC and ORC systems for steel and iron industry.

Waste heat	Cycle	Working fluid	Remarks	Ref.
Waste industrial heat source/98 °C	KC	Ammonia water	Kashima Steel Works install the first commercial KC application of 3.45 MW power generation system	IEA (2002)
Waste industrial heat source/98 °C	KC	Ammonia water	4.5 MW power output is achieved with a water flow rate of 1300 t h^{-1}; The total investment cost is about $ 4 million or about $1.1 MW^{-1}	IEA (2002)
Exhaust gas from coke production/ 221 °C	ORC	Benzene	The net electric efficiency of 11% provides an electricity generation estimate of 80 MW t^{-1} coke	Walsh and Thornley (2012)
Flue gases/529.6 °C	ORC	Siloxane	ORC has a power output of 1.8 MW and a net efficiency of 21.7%	Ramirez et al. (2017)
Residual heat from off-gas of reheating furnace	ORC	Siloxane	The 0.7 MW nominal capacity unit is installed operated by NatSteel in Singapore	Foresti et al. (2010)
Waste heat of off-gas from EAF/ 245 °C	ORC	Siloxane	It is the world first ORC based energy recovery system at an Electric Steel melting plant in Riesa Germany, which could produce 2.7 MW nominal capacity	Bause et al. (2015)
Waste heat from EAF/245 °C	ORC	Siloxanes	An electricity output could reach 0.521 MW and 4.52 MW heat can be supplied for a CHP heat network	Lecompte et al. (2017)
Waste heat from walking beam slab reheat furnace/122 °C	ORC	R245fa	The ORC has a power output of 0.2518 MW and an energy efficiency of 10.2%	Kaşka (2014)

Table 14
Heat to refrigeration cycles for waste heat recovery (Srikhirin et al., 2001; Choudhury et al., 2013).

Cycle	Working pair	Status	Driving temperature/Thermal efficiency	Remarks
Absorption refrigeration	Ammonia-water	Demonstration	Double stage, 75 °C/0.25; Basic, 120 °C/0.55; GAX, 120–160 °C/0.8–1.4.	High pressure, achieve freezing condition
	LiBr-water	Commercial use	Double lift, 60 °C/0.35; Single effect, 90 °C/0.7; Variable effect, 90–135 °C/0.8–1.1; Double effect, 150 °C/1.3.	Suitable for solar energy air conditioning
Adsorption refrigeration	Water-based, e.g. silica-gel water, zeolite water, etc.	Demonstration	Silica-gel water, 55–120 °C/0.6; Zeolite water, 150 °C/0.3 etc.	Simple structure and easy to control
	Ammonia-based, e.g. metal halide ammonia, etc.	Lab-scale	$CaCl_2$ ammonia, 120 °C/0.3–0.4; $SrCl_2$ ammonia, 120 °C/0.3–0.4 etc.	Achieve freezing condition
	Other-based, e.g. AC methanol	Lab-scale	AC methanol, 70–120 °C/0.2.	Achieve freezing condition

relatively high energy efficiency (Zhang et al., 2012). Besides, thermoelectric power generation and thermophotovoltaic systems are being developed that can generate electricity directly from heat (Ando Junior et al., 2018; Utlu and Önal, 2018). Table 12 indicates heat to power cycles for waste heat recovery in terms of heat source type, temperature range, thermal efficiency and capital cost. Rankine cycle and KC have the relatively high suitable temperature range of heat source whereas ORC has a lower temperature range. Thermoelectric generator (TEG) may have a wider temperature range by using various TEG materials. However, this technology has a lower thermal efficiency which hasn't been large-scale demonstrated in the iron and steel industrial section and its capital cost is higher than other power generation technologies (He et al., 2015).

One representative case of KC in steelwork is shown in Fig. 14 which is in Kashima Steel Works of Japan. The demonstration operated by Sumitomo Metals has successfully recovered waste process heat and generating 3.45 MW sustainable power since the September of 1999. More than a decade after installation, KC power plant continues to operate efficiently and reliably (IEA, 2002). For demonstration of ORC systems, Ramirez et al. (2017) presented a project i.e. a large-scale ORC plant in a steel mill which has been installed at ORI MARTIN in Brescia (Italy). Waste heat was recovered from the fumes of the EAF to produce saturated steam which was then delivered to the ORC for power generation. The ORC system has a power output of 1.8 MW and a net efficiency of 21.7%. Table 13 indicates selected case studies of KC and ORC systems in steel and iron industry.

4.2.3. Refrigeration

Thermal driven refrigeration technology is another research hot spot for low grade heat recovery (Xu et al., 2017). Compared with power generation cycle, the relatively low heat source temperature is further utilized due to their operational principle. Various thermal cycles could be adopted to realize cooling effect, e.g. absorption cycle and adsorption cycle.

Absorption refrigeration is basically composed of four components i.e. generator, evaporator, condenser and absorber. Through high pressure and low pressure level, heat could be converted to the cooling effect through generating process of generator and evaporation process of evaporator. The common working pairs are ammonia-water and lithium bromide (LiBr)-water. Ammonia-water working pair could achieve freezing condition and air conditioning condition, which is mainly applied in freezer due to the fact its evaporation temperature can reach as low as −60 °C. Lithium bromide-water working pair could only operate for air conditioning condition. The lowest thermal driven temperature lithium bromide-water absorption chiller is about 90 °C which is much lower than ammonia-water system i.e. about 120 °C (Xu and Wang, 2016). For commercial use, lithium bromide-water absorption chiller has been the most commonly used unit. Similar to absorption refrigeration, adsorption refrigeration is composed of adsorber, desorber, condenser and evaporator. Heat could be converted to the cooling effect through desorption process of desorber in high pressure side and evaporation process of evaporator. It is based on solid-gas reaction using various working pairs in terms of water-based, e.g. zeolite as well as ammonia-based, e.g. $CaCl_2$, which could be generally classified into physical sorption and

Table 15
Selected studies of thermal driven refrigeration in steel and iron industry.

Waste heat	Cycle	Working pair	Another cycle	Research	Remarks	Ref.
Exhaust gas/ 350 °C	Absorption	Ammonia-water	KC	Thermal analysis	Thermal and exergy efficiency are 24.2% and 37.3%	Zheng et al. (2006)
Exhaust gas/ 450 °C	Absorption	Ammonia-water	KC	Thermal analysis	18.2% reduction is realized in energy consumption	Liu and Zhang (2007)
Hot water/ 140 °C	Absorption	LiBr-water	ORC	Simulation	The system reaches thermal efficiency and exergetic efficiency of 38% and 26%	Grosu et al. (2016)
Hot water/ above 75 °C	Absorption	LiBr-water	ORC	Simulation	The simulated thermal efficiency of the combined cycles is improved by 1.5%	Masheiti (2011)
Hot water/ 95 °C	Adsorption	$CaCl_2$—$BaCl_2$—NH_3	ORC	Thermal analysis	Energy and exergy efficiencies are 10.1—13.1% and 18.5—20.3%	Jiang et al. (2014)
Hot oil/140 °C	Adsorption	Silica-gel/AQSOA-ZO2/MOF water	ORC	Thermal analysis	Maximum adsorption power efficiency is 4.3% using silica-gel, while maximum ORC power efficiency is 18.3% using R141b	Al-Mousawi et al. (2017)
Flue gases/ 250 °C	Adsorption	Silica-gel water	ORC	Experiment (Demonstration)	Two systems are cascaded to produce 3 MW electricity and 0.05 MW cooling power	Cao et al. (2016)

chemical sorption. Physical adsorption is driven by Van der Waals force whereas chemical reaction happens between the adsorbent and the adsorbate, and new types of molecules will be formed in the adsorption process (Jiang et al., 2016b; Jiang, L. et al., 2017b). Currently, silica-gel water adsorption chiller is the only commercial product, which has a desorption temperature as low as 55 °C (Saha et al., 1997; Choudhury et al., 2013). Table 14 generally summarizes thermal driven refrigeration cycles for waste heat recovery in terms of working pair, driven temperature, thermal efficiency and their characteristics. Driving temperature and thermal efficiency are all related with constraint temperature. 5 °C evaporation temperature is used for water chiller whereas −15 °C evaporation temperature is mainly adopted for ammonia systems. LiBr-water absorption refrigeration could be applied to the iron and steel industry whereas silica-gel water adsorption system is relative mature technology in real application. Other types are required for further improvement though they have the potential advantages of achieving the freezing condition.

For thermal driven refrigeration, it could be adopted as a separated technology, which is able to be integrated with power generation technology for extra cooling effect. It is generally acknowledged that power and refrigeration cogeneration is a desirable way for waste heat recovery in most applications of steel industry. The cogeneration could be generally classified into two types, i.e. combined cycle and cascading cycle. The combined cycle commonly achieves the cooling and power output in one working cycle (Jiang et al., 2016a) whereas cascading cycle is to produce the respect effect in a half cycle (Jiang et al., 2014). The combined cycle could reach a high thermal efficiency, and cascading cycle can gain a high exergy efficiency of heat source (Jiang et al., 2017). Although various cogeneration research studies have been investigated, less demonstration has been reported in iron and steel industry due to demands, cost, and space. Presenting these studies is to reveal the potentials and advantages of cooling technologies in real application which keeps the consistency and completeness of the heat driven options for thermal network in this paper.

Table 15 shows selected studies and demonstrations of thermal driven refrigeration which tend to be applied in steel and iron industry. Due to unique characteristic of ammonia-working pair, studies of combined cycle based on KC are comprehensively investigated. The cascading system by using the commercial technology is more suitable for real application. Thermal driven refrigeration e.g. LiBr-water absorption chiller and silica gel-water chiller could be good candidates as the second stage of cascading system for power and refrigeration cogeneration.

5. Optimization of mass-thermal network

Energy conversion technologies above are usually considered as a single and one-way mass or thermal utilization. It is worth noting that the integrated steel making site is a complicated network of the units that mutually exchange energy and material. Waste heat sources are distributed in different factories with various energy grades when considering the real situation of iron and steel industry (An et al., 2018). It would cause the difficulties for the efficient use with regard to the demands of heating, cooling, power in a specific industrial zone (Chaer et al., 2018). Thus suitable energy conversion technologies should be not only in single equipment but also in a systematic level. A system approach is required to improve the efficiency of the total site, which results in an optimal mass-thermal network.

5.1. Mass-thermal network of iron and steel industry

For a steelwork industry, there are various plants that have a variety of utilities with different chemical and thermal processes where the raw materials turn into product. Those processes make up a complex manufacturing system, i.e. the mass-thermal network. Large amount of parameters and interactions exist within the network, which are the basic units of the entire system (Zhang et al., 2019). The typical mass network of iron and steel industry is consisted of multiple primary energy saving technologies which are applied to each unit. The goal of mass network is to achieve continuous and compact production to reduce energy consumption and demands (Lu et al., 2016). Fig. 15 shows the main inputs and outputs structure of potential mass network in iron and steel industry. The possible primary energy optimization technologies are considered in this network. Although these technologies are relatively independent in each process, the implementation of one technology may affect the operation potential of another. For example, the recycling by-product gases implies that there is less flue gas for in-plant use. Therefore, various process constrains should be included rather than only considering the balance relationships in the whole system when establishing the mass network.

The secondary energy conversion technologies could be selected in terms of heat sources and heat sinks. Thermal energy storage and energy transportation technologies are indispensable to establish a bridge between sources and ends. The commonly used heat storage technologies for steelwork are all sensible heat storage which are elaborated as follows: regenerator and steam accumulator are used for high temperature heat. The accumulator matches steady steam

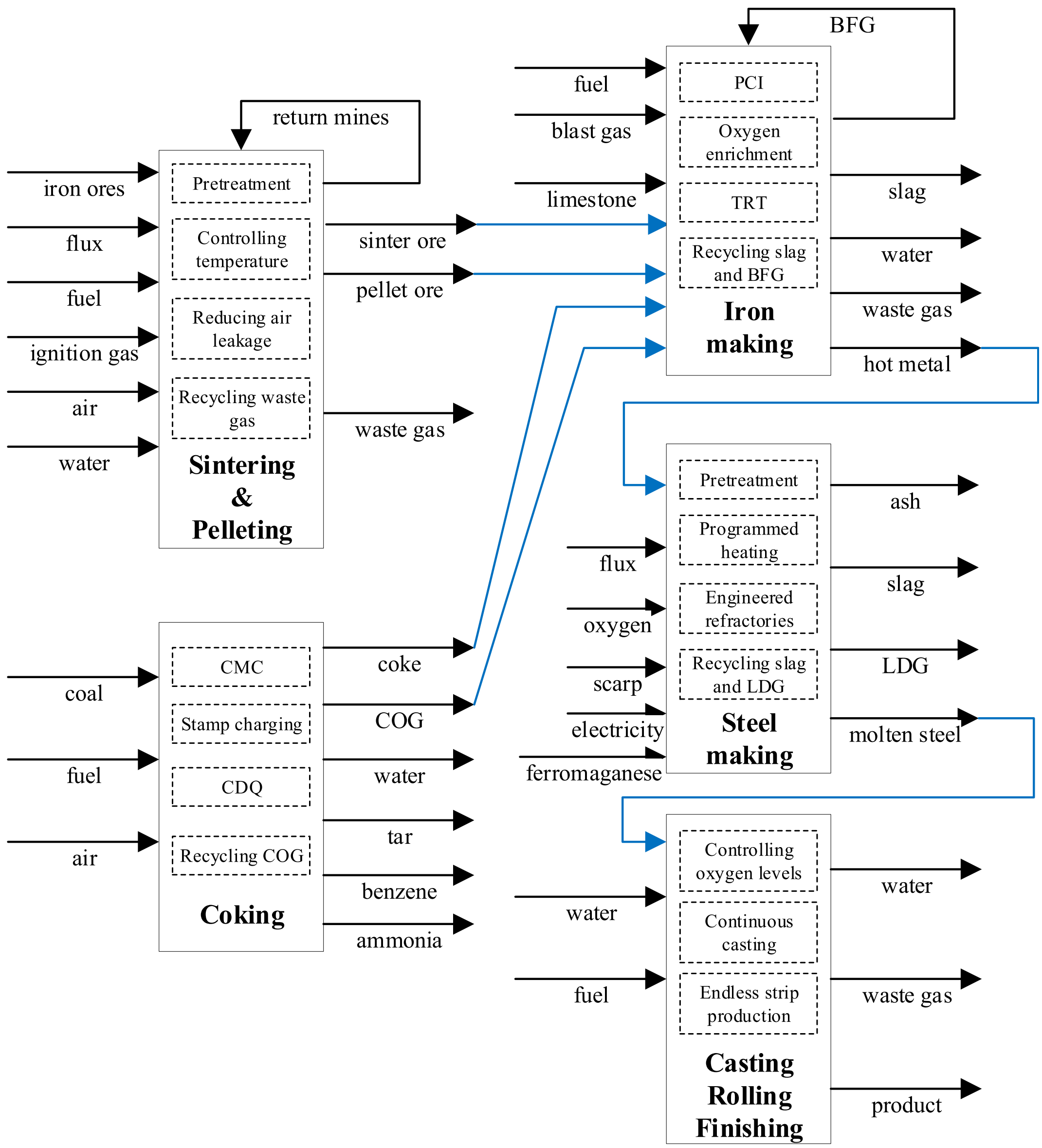


Fig. 15. Main inputs and outputs in mass network (Shen et al., 2018).

production from boilers to the short discharge needs of the vacuum processes, which could be used to balance supply and demand of waste heat (González-Roubaud et al., 2017). For medium and low temperature heat, hot water tank is mainly adopted as an efficient tool (Armstrong et al., 2014). Temperature losses through heat exchangers will be reduced if high quality water is used for circulation. For low temperature waste heat, underground thermal energy storage could be used and supply potentially a high heat capacity at a low cost (Giordano et al., 2016). Except for these commonly used storage technologies, other heat storage technologies would also be good candidates in the future. Chemical energy storage e.g. CaO can be adopted for high temperature heat storage while phase change materials (PCM) e.g. molten salt can be utilized for middle and low temperature heat, which could be combined with the above conventional sensible energy storage technologies (Ortega-Fernández et al., 2015; Chen et al., 2018). Energy transportation technologies are generally interdependent on energy storage methods. Conventional technologies aim at moving the heat transfer fluid to the other locations with a good insulation material. But heat loss significantly increases with the increase of transmission distance and time. Compared with these methods, some novel transportation methods are prospective, for example, absorption liquid transportation (Lin et al., 2009; Xie and Jiang, 2017), adsorption solid transportation (Aydin et al., 2016; Scapino et al., 2017), chemical reactant (Wu et al., 2018) and mobilized PCM (Li et al., 2013; Guo et al., 2016). The schematic diagram of the possible thermal network applications is shown in Fig. 16 (Wang, 2016). Actually, cascading technologies for power and heat/refrigeration cogeneration/tri-generation are most common ways to improve the heat source utilization, which have been gradually applied in steelwork and power plant. (Jiang, L. et al., 2017a). A basic mass-thermal network could be composed of multiple sets of cascading heat flow lines in steelwork by using heat storage and transportation technologies. The defined network should be further optimized in industrial zones based on reasonable optimization methods, which will be elaborated in following subsection.

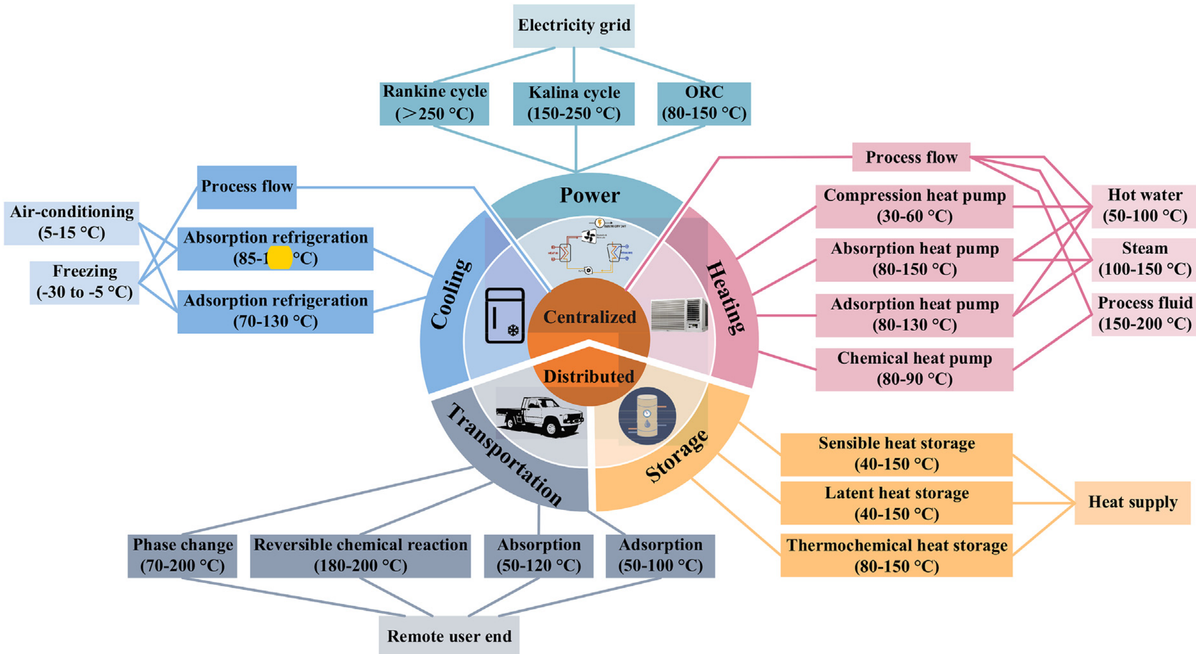


Fig. 16. Schematic diagram of the possible thermal network applications (Wang, 2016).

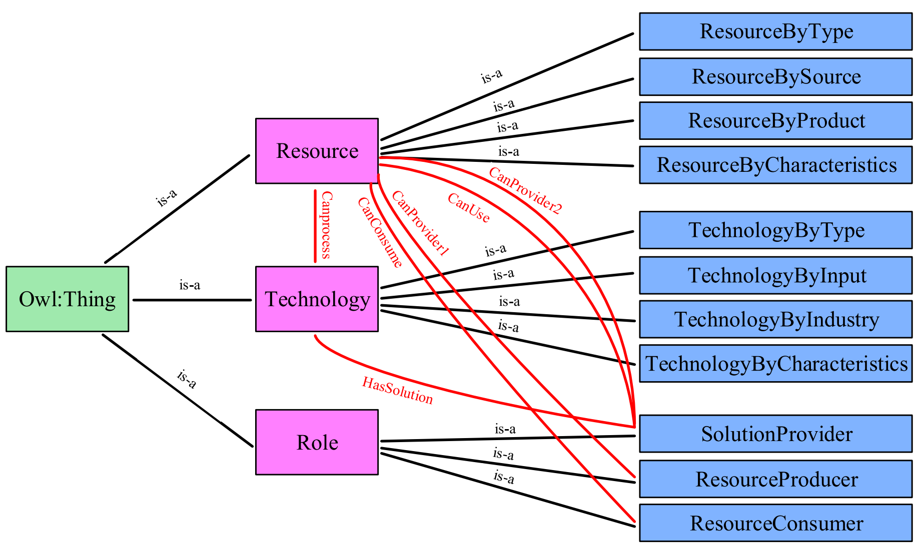


Fig. 17. Schematic diagrams of domain ontology for EIP energy system (Zhang et al., 2017).

5.2. Methods used to optimize the mass-thermal network

The general system optimization methods have been performed in iron and steel industry to avoid sub-optimization and to deliver energy and material efficiency. The conventional optimization methods include exergy analysis, pinch analysis and mathematical programming. Exergy analysis is a suitable tool for problems that involve different types of materials and transformations (Grip et al., 2013b). It is useful when comparing two different production routes and potential resource savings for the same output, for example, crude steel produced from BOF and EAF (Carmona et al., 2019). The exergy efficiency is used to evaluate the industry performance, which can better identify exergy losses along the production chain. Enhanced exergy, exergy economic and exergy environmental analyses are extensions of the conventional exergy analysis (Yılmaz et al., 2019). These methods can be used to assess the overall efficiency of whole processes in the network after optimized by the energy saving technologies. Pinch analysis is a commonly used methodology for minimizing energy consumption by optimizing heat recovery systems, energy supply methods and process operating conditions (Ebrahim and Kawari, 2000). The method allows the calculation of a theoretical maximum level for heat recovery. With more streams available in the consideration of thermal network, more heat can theoretically be recovered in an integrated steel plant (McBrien et al., 2016). It uses the input data to produce hot and cold composite curves. The maximum potential for heat recovery and a theoretical target for integrated recovery can be revealed from the curves, which will be limited by the complexity

Table 16
Selected case studies of optimization in integrated steel mills.

System scope	Optimization method	Remarks	Ref.
Global steel site	Exergy-based resource efficiency	The secondary steelmaking is twice as efficient (65.7%) as ore-based production (29.1%)	Gonzalez Hernandez et al. (2018b)
A reference steel plant	Exergy-based resource efficiency	The mean resource efficiency is 87.9% across 29 days period	Gonzalez Hernandez et al. (2018a)
UK steel sector	Exergy-based resource efficiency and useful exergy efficiency	The overall resource efficiency went from 19% to 32% from 1960 to 2009	Carmona et al. (2019)
A reference steel network	Exergy analysis	The maximum exergy losses occurred in the BF and the exergy efficiency of iron making is 42.19% after industrial symbiosis implementation	Wu et al. (2016)
A reference power plant	The enhanced exergy analysis	The traditional and the enhanced exergy efficiencies of the system are 60.7% and 83.7%, respectively	Yılmaz et al. (2019)
A reference steel plant	Pinch analysis	Integrated heat recovery with conventional heat exchange could save 2.5 $GJ \cdot t^{-1}$ hot rolled steel	McBrien et al. (2016)
A reference steel plant	Pinch analysis	Thermal energy flows dominate the local energy system; The distance will limit a connection between the energy systems	Grip et al. (2013a)
A reference steel plant	Pinch analysis	The heat under 300 °C can be used to develop power generation systems	Matsuda et al. (2012)
Italian steelwork gas network	Multi-objective optimization	An optimized off-gas exploitation can be devised	Maddaloni et al. (2015)
A reference steel plant	Energy intensity optimization model	Sinter ore grade has significant impact on energy intensity	Lu et al. (2016)
A hot rolling strip production	Linear and nonlinear programming methods	After optimization, the energy consumption can maximumly decrease by 3.4%	Shen et al. (2018)
By-product gas system	Dynamic mixed integer linear programming model	The total cost can be reduced by 7.5%	Kong et al. (2010)
A reference EAF pathway	Decision support tool and key performance indicators evaluation tool	Scrap quality strongly affects the monitored energy and environmental parameters	Matino et al. (2017a)
Italian integrated steelworks	Mixed integer linear programming	By-products management could provide advantages to the companies to the “zero waste” target	Matino et al. (2017b)
A reference steel plant	Full length material-energy nexus flow combined model	After optimization, the total specific energy consumption and direct CO_2 emissions can be decreased by 14.07% and 6.65%, respectively	Zhang et al. (2019)
A reference energy system	Exergy analysis, pinch analysis and mathematical programming	Pinch and exergy studies could suggest changes that are tested by mathematical programming	Grip et al. (2013b)

of the network of heat exchangers required in practice (McBrien et al., 2016).

Since the network structure is unknown and must be optimally exchanged resources between the plants, this requires the use of mathematical programming methods to formulate a network that includes all the potential mass and energy connections (Pan et al., 2016). Through mathematical programming, the optimization can be defined by a set of equations, the equality/inequality constraints, and an objective function. Various mathematical models for the optimization of whole process system have been established by analysing different optimization objectives. For example, an ontology-based approach for Eco-industrial park (EIP) knowledge management is proposed as shown in Fig. 17 (Zhang et al., 2017). EIP energy system ontology can be treated as a domain ontology which treats all things in EIP belonging to resource, technology and role. The relationships between each one of them are defined in the domain ontology. A dynamic mixed integer linear programming model for multi-period optimization of by-product gases is used to optimize distribution of gases in the integrated iron and steel plant (Kong et al., 2010). The proposed model simultaneously optimizes the by-product gases distribution, cogeneration system as well as iron and steel making system. The combination of linear programming and nonlinear programming methods and “e-p” analysis is applied to obtain the optimal burdening proportions and operating parameters in BF process (Shen et al., 2018). On the basis of industrial metabolism concept, a model is used to analyse the energy flows by using genetic algorithm. The model provides a concise framework, which can be adopted to examine the energy flows, especially focusing on the recovery and utilization of secondary energy (Sun et al., 2016). All of the optimization models mentioned above will be put forward based on the material and energy flow which focus on saving energy and reducing emissions for iron and steel industry.

Table 16 shows selected studies of various optimization methods applied in steel and iron industry. The proposed methods provide management with important information for optimization in different levels of system. These results are limited by the practice in the actual plant. Further researches are required to apply these methods into reality to verify their validity and to find the limitations.

Among all the related methods, the basic guideline for mass-thermal network optimization aims to target the maximum energy potentials and to develop economically optimal networks connecting recoverable utilities and utility systems, which is generally composed of five steps (Stijepovic et al., 2012). The first step is data acquisition. This step is to find out all the plants and processes in the industry, and the number of plant and utility, temperature and pressure of each utility, hot and cold steams, the distance for heat transportation and so on. The second step is to determine all the energy sources and sinks to indicate the energy potentials by using exergy indicator. Many specialized simulation software tools (Aspen Plus™ and GateCycle™) will be used at this step, which provides clear operating process and detailed data for plant integration. The third step is to establish a link between the origin and other different utilities which may include new recoverable utilities. Then the fourth step is to determine the maximum potential. The final step is to design optimal energy recovery and reuse networks. The multi-objective optimization based on mathematical programming will be considered in this process.

The utilization is quite complicated if various heat sources and different demands are required to be satisfied. Therefore, high-quality integration of the system should be accomplished to realize high efficient use of industrial waste heat by means of energy network utilization, which includes heating, power generation, cooling, and storage and transportation technologies. The basic guideline for the whole iron and steel industry is to improve every detailed utilization of primary energy for mass network optimization. For thermal network of heat recovery, energy integration should be first conducted. Finally, multiple objectives application and the extreme values of the operating parameters would be determined to make the optimal target or other optimized parameters such as minimum CO_2 emission and the lowest cost.

6. Conclusions

Iron and steel industry consumes considerable primary and secondary energy. Lots of the energy efficient improvements are developed in terms of steel products, technologies and operating practices which could more or less reduce the energy consumption, respectively. To further explore the potentials of energy saving, the demands and supplies should be considered from an overall perspective.

In this paper, a comprehensive research framework of mass-thermal network in iron and steel industry are developed and the contributions could be classified into three levels. First, the overarching energy consumption in iron and steel industry is present and the potential of secondary energy is demonstrated to be highlighted. Second, the independent and interdependent relationship between mass and thermal network are clearly reviewed and compared based on primary energy reduction methods and secondary energy savings technologies. The former technologies aim to reduce the energy demands while the latter technologies consider the conversion of thermal energy. The concept of mass-thermal network in iron and steel plant is established. Eventually, the general guideline i.e. 5-step method is summarized to optimize the mass-thermal network. Thus multiple objectives application and the extreme values of the operating parameters should be determined to make the optimal energy target. With the potentially wide use of efficient sustainable technology for iron and steel industry, the mass-thermal network and its optimization will be considered as a method to solve the problem of energy savings. In the future research, a set of mathematical models are necessary to be built for compensating the basic optimization method in some cases.

Declaration of competing interest

The authors declared that they have no conflicts of interest to this work. We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

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