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A Sankey Diagram Approach to Quantifying Industrial Residual Energy in China

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The industrial sectors are the largest energy consumers of China, accounting for more than 60 % of China's overall energy consumption. However, a large part of energy in the industrial sector is not used efficiently, and there is great potential for enhancing energy utilization efficiency. This paper is the first work that explicitly addresses the conception of China's industrial residual energy, which includes the definition, classification and quantification of twelve high-consuming industry sectors in China. Sankey Diagram approach is applied to analyse the current situation of IRE that can intuitively reveal the relations among specific forms and the reason why China has not utilized IRE efficiently, based on which we propose the policy suggestions. The energy flows are illustrated via Sankey Diagrams, which explicitly indicate stages with huge energy waste thus great potential for improving. Results show that the iron and steel sector has the largest potential for energy recovery, amounting to approximately 300 Mt coal equivalent per year. The energy recovery potential in each sector is further divided into three levels according to technical difficulty, namely full potential, technically recoverable (TR), and already utilized. Based on the results, prioritizing development of some energy recovery technologies is proposed, including coke dry quenching, combined cycle power generation from industrial residual gas, and power generation with low temperature waste heat during cement production, with an expected annual energy saving of 120 million tonnes coal equivalent.

1. Introduction

China is the largest energy consumer around the world, and its energy utilization efficiency still has large potential for improvement. In the energy-extensive industries, China spends 15 % more energy than international advanced level with the same production value. In China, high-energy-consumption industries mainly include Smelting and Pressing of Ferrous Metals, Smelting and Pressing of Non-ferrous Metals, Manufacture of Non-metallic Mineral Products, Manufacture of Raw Chemical Materials and Chemical Products, Process of Petroleum, Manufacture of Textile and Manufacture of Paper, which totally consume 79 % of total industrial energy, 45 % of China's total energy consumption as well (Zhou et al., 2010).
Industrial residual energy, as a kind of secondary energy, refers to the pressure energy and thermal energy (both sensible and potential) produced by certain industrial processes. The residual energy is often carried by specific mediums, such as smoke, cooling water, hot production, hot slag and high-pressure gas, all of which make up a considerable heat source, namely industrial residual energy (Zhang et al., 2013). Different from most of the developed countries, China is a late starter in industrial process, and many industrial sectors have not utilized the energy resources in a best way, generating plenty of exploitable mediums. Some Chinese industries have been concentrating on proceeding industrial residual energy utilization, but the overall performance has been unknown. Although many researches have been focusing on specific techniques of utilizing industrial residual heat, there isn't any quantitative analysis of the overall situation. In this work, we are going to illustrate the current residual energy utilization situation of industrial sectors in a quantitative way.

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2. Overview

IRE concentrates in the industrial mediums, which contains much available energy. However, we can't utilize all IRE because of the space limitation of industrial plants and high proportion of low-temperature mediums. For figuring out how much IRE we can use, we need to analyse the specific forms of IRE in detail. IRE can be classified into sensible heat, combustible heat and pressure energy, which behaves in vapour, liquid and solid forms. In this section we are going to illustrate the specific forms of every involved industrial sector. Specific IRE forms are shown from Table 1 to Table 5.

Table 1: IRE forms of iron and steel industry

Forms	Process	Category	State of matter	Temperature (°C)
Hot Coke	Coking	Sensible heat	solid	950 ~ 1,050
Coke Oven Gas	Coking	Sensible heat; combustion heat	vapor	650 ~ 850
Coke Oven Smoke	Coking	Sensible heat	vapor	180 ~ 230
Hot Sinter	Sintering	Sensible heat	solid	650 ~ 800
Sintering Smoke	Sintering	Sensible heat	vapor	150 ~ 200
Hot Pellet	Pelletizing	Sensible heat	solid	350 ~ 500
Pelletizing Smoke	Pelletizing	Sensible heat	vapor	100 ~ 200
Blast Furnace Slag	Iron making	Sensible heat	solid	1,400 ~ 1,500
Blast Furnace Gas	Iron making	Sensible and combustible heat; pressure energy	vapor	300
Stove-exhausting Gas	Iron making	Sensible heat	vapor	200 ~ 300
Hot Steel Slag	Steel making	Sensible heat	solid	1,400
Converter Gas	Steel making	Sensible heat; combustion heat	solid	> 1,000
Converter Smoke	Steel making	Sensible heat	vapor	1,400 ~ 1,600
Steel-rolling Hot Blast Furnace Smoke	Steel rolling	Sensible heat	vapor	350 ~ 400
Cooling Water	All	Sensible heat	liquid	< 100
Hot Coke	Coking	Sensible heat	solid	950 ~ 1,050

Table 2: IRE forms of electrolytic aluminum industry

Forms	Process	Category	State of matter	Temperature (°C)
Electrolysis Gas	Aluminum electrolysis	Sensible heat	vapor	100 ~ 200
Rotary Kiln Smoke	Production of anode carbon	Sensible heat	vapor	800 ~ 1,100
Baking Furnace Smoke	Production of anode carbon	Sensible heat	vapor	150 ~ 250
Electric Forge Furnace Gas	Production of cathode carbon	Sensible and combustible heat	vapor	300 ~ 400

3. Quantification

3.1 Full potential

Having already shown different forms of IRE, in this part, we are going to give a universal quantification criteria of full potential in terms of sensible heat, combustible heat and pressure energy. Based on the quantification standard, the Sankey Diagram of IRE full potential will be given for showing the general pattern of China.

As we know, sensible heat can be measured only by calculating the enthalpy difference between two states of IRE mediums, namely upper limit and lower limit. The upper limit naturally refers to the state of IRE mediums produced by industrial processes, as has been shown in section 2. Considering the rapid development of low-temperature Rankine cycle and heat pump technology, we set 30 °C as the lower limit, which means the enthalpy higher than the state of 30 °C is the sensible heat quantity. Combustible heat quantity refers to the energy that IRE mediums can release when it is burned. Pressure energy quantity is the maximum work when high-pressure mediums drive the turbine.

Table 3: IRE forms of synthesis ammonia industry

Forms	Process	Category	State of matter	Temperature (°C)
Upward Gas	Gas generation section	Sensible heat	vapor	320 or > 600
Downward Gas	Gas generation section	Sensible heat	vapor	270
Blow-out Air	Gas generation section	Sensible and Combustible heat	vapor	310
Gas Generation Slag and Debris	Gas generation section	Combustible heat	solid	
Gasifier Jacket	Gas generation section	Sensible heat	solid	
Shift Gas	Conversion section	Sensible heat	vapor	90
Cuprammonium	Refining sector	Sensible heat	liquid	78
Synthesis Gas	Synthetic section	Sensible heat	vapor	350

Table 4: IRE forms of glass industry

Forms	Category	State of matter	Temperature(°C)
Furnace Body	Sensible heat	solid	> 150
Tin Bath Body	Sensible heat	solid	200
Melting Furnace Smoke	Sensible heat	vapor	450 ~ 550
Annealing Furnace Exhaust Air	Sensible heat	vapor	280 ~ 500
Circulating Cooling Water	Sensible heat	liquid	35

Table 5: IRE forms of other industrial sectors

Industry sector	Forms	Category	State of matter	Temperature(°C)
Oil Refining	Oil products	Sensible heat	liquid	70 ~ 200
Oil Refining	Smoke	Sensible heat	vapor	< 200
Oil Refining	Waste Water	Sensible heat	liquid	< 150
Oil Refining	Steam	Sensible heat	vapor	
Oil Refining	Flare Gas	Combustible heat	vapor	
Cement	Exhaust	Sensible heat	vapor	< 400
Carbon Black	Off-gas	Combustible heat	vapor	
Textile Dyeing	Condensate Water	Sensible heat	liquid	100
Textile Dyeing	Cooling Water	Sensible heat	liquid	60
Textile Dyeing	Dye Vat Water	Sensible heat	liquid	60 ~ 70
Textile Dyeing	Boiler Smoke	Sensible heat	vapor	> 220
Textile Dyeing	Calibrator's Waste gas	Sensible heat	vapor	> 120
Paper Making	Boiler Smoke	Sensible heat	vapor	110 ~ 145
Paper Making	Hot Air	Sensible heat	vapor	65
Calcium Carbide	Furnace Smoke	Sensible heat	vapor	350~600
Calcium Carbide	Fused Products	Sensible heat	solid	2,000
Sodium Carbonate	Calcinatory Gas	Sensible heat	vapor	120
Vitriol	Sulfur Dioxide Gas	Sensible heat	vapor	950
Vitriol	Sulfur Trioxide Gas	Sensible heat	vapor	400
Vitriol	Oil Products of Vitriol	Sensible heat	liquid	110~120
Copper Refining	Reverberatory Furnace Smoke	Sensible heat	vapor	1,200
Copper Refining	Flash Furnace Smoke	Sensible heat	vapor	1,300
Copper Refining	Converter Smoke	Sensible heat	vapor	1,100
Copper Refining	Anode Furnace Smoke	Sensible heat	vapor	1,400
Copper Refining	Electric Furnace Smoke	Sensible heat	vapor	270
Copper Refining	Electric Furnace Slag	Sensible heat	solid	> 1,200

Specific Formulas are given below:
Sensible heat

$$Q_s = M_i \int C_i \, dT = M_i \times \Delta H \tag{1}$$

M_i,C_i, dT and ΔH are mass, specific heat capacity, temperature difference and enthalpy difference of IRE mediums respectively.
Combustible heat:

$$Q_c = M_i \times q_i^m = V_i \times q_i^v \tag{2}$$

M_i,V_i,q_i^m and q_i^v are mass, volume, combustible heat per unit volume and combustible heat per unit mass of IRE mediums respectively.
After the calculation based on above criteria, this paper uses the Sankey Diagram to show the results of full potential, as shown in Figure 1.

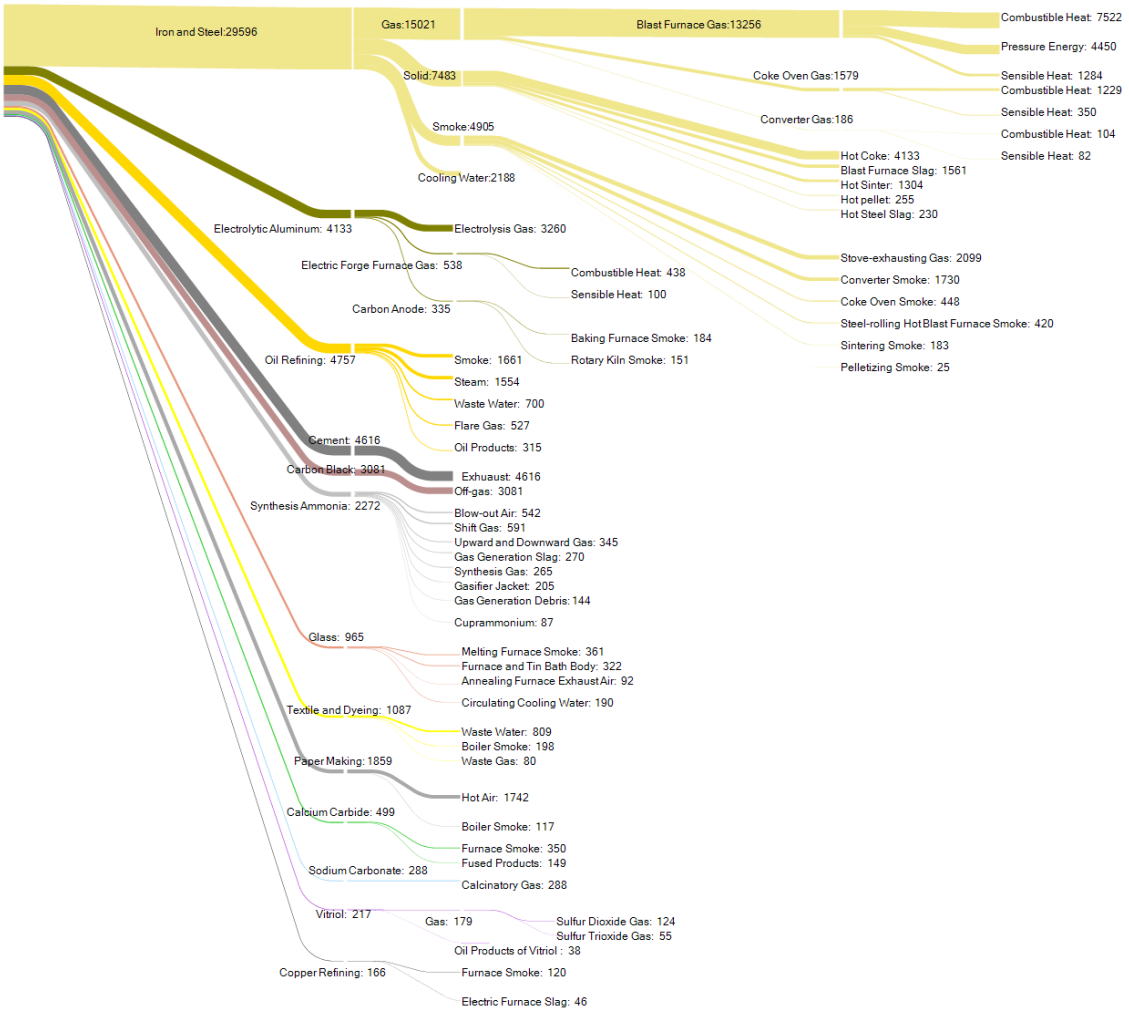

Figure 1: Sankey Diagram of China's IRE full potential

3.2 Current status of utilization

In this part, according to the investigation of China's industry, we will show the Sankey Diagrams of IRE utilization of different industrial sectors. Due to space limitation, we choose iron and steel industry and synthesis ammonia as examples to show how Sankey Diagram approach works in this study, as shown from Figure 2 and Figure 3. In every Sankey Diagram, yellow parts represent the full potential, brown parts representing the technically recoverable, blue parts on behalf of already utilized residual heat, we can intuitively find the key problems of IRE recovery from these Sankey Diagrams. All the units are 10,000 t of coal equivalent. Figure 4 shows the overall utilization status of China's industrial residual energy.

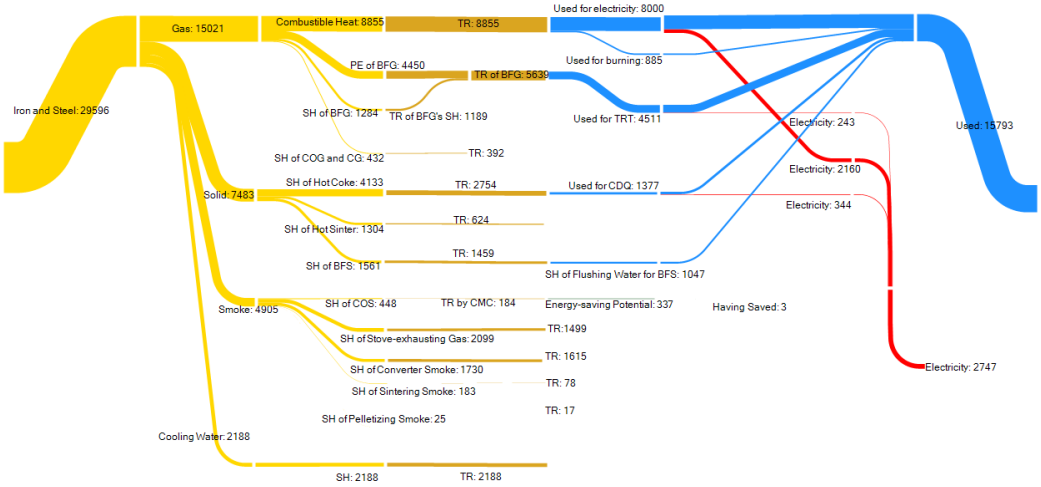

Figure 2: Sankey Diagram of iron and steel industry
PE: pressure energy; BFG: blast furnace gas; SH: sensible heat; COG: coke oven gas; CG: converter gas; CDQ: coke dry quenching; BFS: blast furnace slag; COS: coke oven smoke; CMC: coal moisture control

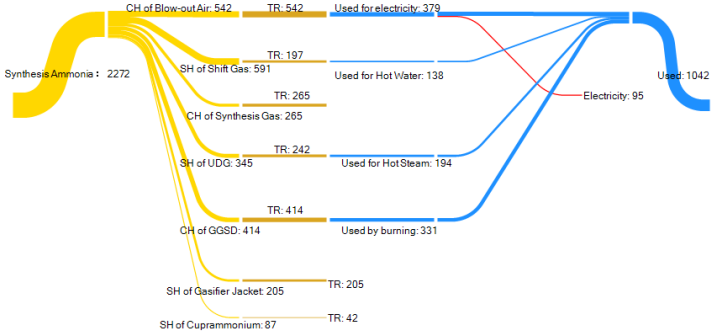

Figure 3: Sankey Diagram of synthesis ammonia industry
CH: combustible heat; UDG: upward and downward gas; GGSD: gas generation slag and debris

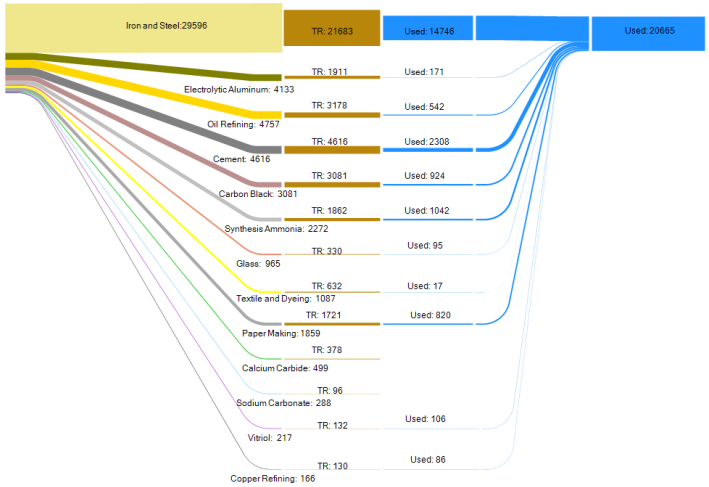

Figure 4: Overall Sankey Diagram of China's industrial residual energy utilization status

3.3 Analysis

From the gap between different stages among every industry sector, we can easily know the problems of IRE utilization. From Figure 2, one can know the sensible heat of hot pellet, hot steel slag and steel-rolling hot blast furnace, which amounts to 9 Mt of coal equivalent, can't be utilized in certain ways (Wang et al., 2014). Meanwhile, some good using methods of IRE have been proved to be effective and feasible, such as coal moisture control technique and using hot waste water for heating (Wang et al., 2014), having not been popularized because of reforming difficulty and expensive cost, which can save at least 30 Mt of coal equivalent. As far as iron and steel industry is concerned, it's needful to apply effective using methods into practice and develop the utilization potential of sensible heat at present.

From Figure 3, one can know the sensible heat of shift gas, which amounts to around 6 Mt of coal equivalent, can only be used in one third. Meanwhile, the combustible heat of synthesis gas, which is around 4 million coal equivalent, has not been utilized (Xi, 2011). In conclusion, it's necessary to develop the low-temperature residual energy of shift gas and burn synthesis gas for a proper purpose.

4. Conclusions

Currently, there are 500 Mt of coal equivalent full potential of IRE in China, of which 400 Mt are technically recoverable, and 200 Mt have already been utilized. Among the 13 industrial sectors, iron and steel industry is the most potential, whose full potential is about 300 Mt of coal equivalent. The paper is the first work that introduces the specific forms of IRE throughout all the high-consuming industry sectors in China, before which all papers about IRE are focusing on one certain area. From the Sankey Diagrams and forms shown above, this paper reveals the current situation of IRE and intuitively shows the parts where China has not utilized IRE efficiently. Current problems of IRE mainly lie in the development of utilization potential and promotion of feasible using methods, the specific data of which are shown in Sankey Diagrams.

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