Primary diagnosis of energy efficiency in an integrated steel plant, based on intensive energy-saving methodology. Part 2

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The energy efficiency of the integrated steel plant is studied basing on the intensive energy conservation methodology. The primary diagnostics of the energy efficiency of the integrated steel plant is carried out. The boundaries of the research object are established from iron ore deposits to finished cold-rolled steel sheet. The thermophysical heat absorption of materials and intermediates within the boundaries of a closed heat engineering complex has been estimated. The energy intensity of the cold-rolled steel sheet within the same boundaries has been calculated.

Efficiency of production was estimated by comparing heat consumption and energy intensity. The complete intensive energy conservation reserve in the complex has been determined. Reserve structure is studied and directions of its implementation are discussed. It is shown that the most complete implementation of the energy-saving reserve is possible only with the transition of a new generation of steel engineering and technology.

Key words: energy efficiency, integrated steel plant, intensive energy saving methodology, graph theory, network flows, heat consumption and energy intensity, primary diagnosis of energy efficiency, energy saving reserve and its structure, directions of technical progress of metallurgical engineering and technology.

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Introduction

The energy efficiency of an integrated steel plant is of great practical interest due to the large economic scale of production and high specific energy consumption for the production of final products. These problems have been studied by many authors using various methods [1-7].

In this paper, energy efficiency is investigated based on the Intensive Energy Saving Methodology (IESM). The boundaries of the object of study are established from iron ore deposits to the finished steel cold-rolled sheet. The research object is presented in the form of a directed graph, the flows of materials in this network are calculated [1] and they are the initial data for this study.

Heat consumption calculation

Technological heat consumption (heat absorption) of the processed materials is determined only by their energy state and does not depend on energy sources, energy supply chains or heat transfer efficiency.

This value is determined only by the actually achieved temperature and thermal state of the material, and its calculations require thermophysical data on the internal energy or enthalpy of materials, or the heat capacity of materials as a function of temperature over a given interval.

Thus, the initial data for calculating the technologically necessary heat consumption are: the temperature schedule of the technology, the thermophysical properties of the materials, the integral flow (through) coefficients of the consumption of materials on the final steel sheet which were calculated earlier [1]. Known published data [8, 9] on the temperatures of the processed substances are summarized in **Table 1**.

Known reference data on the thermophysical properties of the processed materials, the temperature schedule of processing, explicit calculation schemes of the complex and integral (through) coefficients, make it possible to calculate the physical heat consumption of the processed materials in the same complex in the production of the same products for comparison with the energy intensity.

The heat consumption of materials during their heat treatment in the i-th technological operation can be calculated by the formula:

$$(q_{tp})_i = \sum_j [m_{i,j} \cdot \Delta h_{i,j}(\Delta t_{i,j}) + (q_{end})_j - (q_{ex})_j] \qquad (1)$$

where:

$(q_{tp})_i$ - heat consumption in the i-th operation, J;

i - the number of technological operation;

j – the material number in the i-th technological operation;

$m_{i,j}$ - the mass of the material subjected to heat treatment, kg;

$\Delta t_{i,j}$ – the temperature range of the material subjected to heat treatment, K;

$\Delta h_{i,j}$ – the change in the enthalpy of the material, subjected to heat treatment, in the temperature range $\Delta t_{i,j}$, J/kg;

$(q_{end})_j$ - the heat of endothermic reactions in the temperature range of the heat treatment $\Delta t_{i,j}$, J/kg;

$(q_{ex})_j$ – the heat of exothermic reactions in the temperature range of the heat treatment $\Delta t_{i,j}$, J/ kg;

Table 1. **Data on the temperature schedule for the processing of iron ore into steel sheet**

№	Ttechnological operation	Temperature level of processes
1	sintering of sinter and pellets	1400 °C
2	*sinter and pellet cooling*	T_a
3	smelting reduction	1500 °C
4	oxidative refining	1600 °C
5	hardening of liquid steel	1500 °C
6	liquid steel casting	1550 °C
7	*cooling ingots to*	T_a
8	heating ingots for rolling	1250 °C
9	reduction of ingots into slabs	1000 °C
10	*cooling slabs to*	T_a
11	heating slabs for rolling	1250 °C
12	hot rolling to coils	900 °C
13	*cooling coils to*	T_a
14	continuous etching	90 — 95 °C
15	cold rolling	150 - 200 °C
16	heat treatment	800 °C
17	*cooling coils after heat treatment to*	T_a

where T_a is the ambient temperature, °C.

Table 2. **Heat consumption on the final sheet**

Heat consumption	OHF			BOF			EAF		
	q_{tp}	K_i	$q_{tp} \cdot K_i$	q_{tp}	K_i	$q_{tp} \cdot K_i$	q_{tp}	K_i	$q_{tp} \cdot K_i$
	kJ/t semi-product	t / t semi-product	kJ/t sheet	KJ/t semi-product	t / t semi-product	kJ/t sheet	kJ / t semi-product	t / t semi-product	kJ/t sheet
Cold rolled sheet	560	1.075	602	560	1.075	602	560	1.075	602
Hot rolled sheet	875	1.115	976	875	1.115	976	875	1.115	976
Ingot slab	875	1.333	1166	875	0	0	875	0	0
Liquid steel	749	1.388	1040	0	1.162	0	1518	1.162	1764
Cast iron	8030	0.938	7532	8030	1.049	8423	8030	0.118	946
sinter	2229	0.74	1649	2229	0.828	1846	2229	0	0
Pellets	3180	0.844	2684	3180	0.943	2999	3180	0.106	337
Coke	3360	0.419	1408	3360	0.468	1572	3360	0.049	166
TOTAL	q_{tp}		**17057**			**16418**			**4790**

The total heat consumption for the final product can be calculated taking into account the integral (through) coefficients (**Table 2**):

$$Q_{tp} = \sum_i (q_{tp})_i \cdot K_i \qquad (2)$$

Thus, the thermophysical necessary heat consumption of materials in the processes of production of cold rolled sheet from iron ores for open-hearth furnace (OHF) and basic oxygen furnace (BOF) routs is close to 16 - 17 MJ/t, and for electric arc furnace (EAF) it is an order of magnitude lower: 4.79 MJ/t of sheet.

For the primary diagnosis of energy efficiency, it is necessary to compare these values with the actual energy consumption along the considered routes – i.e. energy intensity.

Energy intensity calculations

The calculation of the energy intensity of the final products of the steel industry is based on the following principles.

The energy intensity of each intermediate consists of at least the following three main components:

- the energy intensity of the input streams of intermediates calculated earlier,
- the energy intensity of additional materials, the energy intensity of which was not calculated, but was estimated on the basis of industry-wide data,
- energy equivalents of direct fuel and transformed energy costs: heat, water vapor, compressed air, air separation products, electricity, etc.

If the number of incoming flows whose energy intensity was calculated earlier is *N*, the number of additional materials, the energy intensity of which was not calculated, but was estimated on the basis of industry-wide data – *M*, The amount of direct energy costs – L, then:

$$E = \sum_{i=1}^{N} m_i \cdot e_i + \sum_{j=1}^{M} g_j \cdot e_j + \sum_{k=1}^{L} q_k \cdot e_k \quad (3)$$

where:

E - the energy intensity of the current intermediate of the production of cold rolled steel sheet, kgce/t [kgce = kilogram of coal equivalent = 29,309 MJ];

i – the number of the input stream of the previous intermediate with the calculated energy intensity;

N – the number of incoming intermediates;

j – the number of the incoming stream of additional materials from outside the complex;

M – the amount of incoming additional materials;

k - the energy agent number;

L – the amount of energy agent used;

m_i - the mass of the incoming stream of the previous intermediate, t (or kg);

e_i - energy intensity of the previous intermediate product kgce/t;

g_j - mass flow of additional materials, t or kg;

e_j - assessment of the energy intensity of additional materials, kgce/t;

q_k - the amount (in different units) of energy agent used, m^3/kg (kW·h or J/Cal);

e_k - the energy equivalent of the energy source in fuel equivalent, kgce / unit.

For example, when calculating the energy intensity of a concentrate, the following flows are taken into account (**Table 3**).

In this case:

- one incoming intermediate product flow (commercial ore), for which there is an assessment of energy intensity; $i = 1$; $N = 1$;
- three incoming streams of additional materials that are produced outside the complex under consideration: metal balls, rods and lining for grinding the incoming ore, for which there is an assessment of energy intensity, $j = 1,2,3$, $M = 3$;
- two used energy agents: electricity and water, for which there are energy equivalents; $k = 1,2$, $L = 2$.

The results of energy intensity calculations for the indicated dependencies and algorithms and for all three technological routes are given in **Table 4**.

So, the OHF steel is less energy intensive than BOF steel by almost 200 kgce/t, due to the higher proportion of scrap processed.

However, due to the significant cutting of the head and tail of the ingots rolled to slab, the energy intensity of the resulting slabs is practically compared with the energy intensity of the slabs of continuous casting of BOF steel: 1035 and 1038 kgce/t of slab.

As a result, the energy intensity of the cold-rolled sheet along the BOF- CCM route is the biggest due to the high energy intensity of the BOF steel.

The obtained data on the energy intensity of the final products allow, in accordance with the IESM to calculate [1] energy efficiency of the metallurgical complex:

$$\eta_1 = Q/E \quad (4)$$

Table 3. **Calculation of the energy intensity of the iron ore concentrate**

	Concentrate	Consumption of material per 1 ton of product, t/t	Energy intensity of the material, kgce/t	Material contribution to the energy intensity of the product, kgce/t of concentrate
i=1	ore, t/t	2.227	4.635	10.322
j=1	balls, kg	1.460	1	1.460
j=2	rods, kg	0.384	1	0.384
j=3	lining, kg	0.176	1	0.176
k=1	electricity, kW·h	58.14	0.377	21.919
k=2	water, m^3	19.5	0.105	2.048
Total				36.309

Table 4. **Energy intensity of semiproducts of sheet production and final products, kgce/t**

Semiproducts	OHF-ingots	BOF- CCM	EAF- CCM
Ore	*4.635*	*4.635*	*4.635*
Concentrate	*36.31*	*36.31*	*36.31*
Coke	*1180*	*1180*	*1180*
Pellets	*111*	*111*	*111*
Agglomerate	*119*	*119*	*119*
Scrap	*8*	*8*	*8*
Cast iron	*1042*	*1042*	*1042*
Liquid steel	**843**	**1038**	**714**
Ingots	**843**	**-**	**-**
Slabs	**1035**	**1038**	**714**
Hot rolled products	**1191**	**1197**	**859**
Cold rolled sheet	**1395**	**1401**	**1038**

where CCM – continuous casting machines.

Table 5. **Complete intensive energy conservation reserve and primary diagnostic report on energy efficiency of various technological routes for the production of cold rolled steel sheet**

Cold Rolled Steel Sheet	Formulas	OHF - molds	BOF - CCM	EAF - CCM	OHF - molds	BOF - CCM	EAF - CCM
		Kgce/ton			GJ/ton		
Heat consumption	Q	582	560	**163**	17.06	16.42	**4.79**
Energy intensity	E	1395	**1401**	1038	40.87	**41.07**	30.41
Reserve	R = E- Q	813	841	**874**	23.82	24.65	**25.62**
Efficiency	$\eta = Q/E$	0.4173	0.3998	0.1575	0.4173	0.3998	0.1575
Efficiency, %		41.73	39.98	**15.75**	41.73	39.98	**15.75**

Table 6. **Complete reserve of energy saving and primary diagnostic report on energy efficiency of various technological routes for the production of raw steel.**

Raw Steel	OHF - molds	BOF - CCM	EAF - CCM
Energy intensity			
kgce	843	**1038**	714
GJ	24.72	**30.42**	20.94

where Q — heat absorption of the finished product, kgce/t sheet;

E — the energy intensity of the finished steel cold-rolled heat-treated sheet, kgce/t sheet.

as well as a full reserve of energy saving:

$$R = E - Q \quad (5)$$

where R - the full reserve of energy conservation in a closed heat production complex for the production of finished steel cold-rolled sheet, kgce t/t sheet.

The results are presented in **Table 5**.

Similar results calculated only for crude steel, for comparison with known published data, are presented in **Table 6**.

The bold type in the table indicates the extreme values of the indicators.

Results and discussion

Thus, the production of steel sheet from iron ores has significant reserves of energy conservation, amounting to 24 - 26 GJ/t.

The total energy efficiency of OHF and BOF steel per final sheet is approximately 40 %.

Noteworthy is the low energy efficiency of the EAF: about 16 %.

High values of the energy conservation reserve stimulate an intensive search for directions and methods for its implementation.

For all three routes, the total reserve of energy conservation is comparable, but the structure of these reserves is completely different.

In the OHF-ingots steel rout the main regulator of energy efficiency indicators is the share of melted scrap, which can lie usually in the range of 40—70 %, or more - up to 100 %.

The second part of the reserve on this route is the obvious transition from ingot to continuous casting. This will eliminate all the costs of heating the ingot before rolling it into a slab, exclude the edging of the ingot rolling and diminish the total energy intensity of the cold rolled sheet to 1203 kgce/t.

In this version of OHF-CCM, cold-rolled steel sheet can occupy a middle position between the BOF and EAF routes by the value of an energy intensity. At the same time, in the OHF variant there is still a reserve of energy conservation in the form of a possible increase in the share of melted scrap.

However, the share of OHF steel worldwide is steadily declining, which weakens the relevance of energy conservation on this route.

Currently, the BOF process is the dominant method of steel production but the share of smelted scrap has fundamental limitations and cannot exceed 20-25 % (without special measures), which excludes this regulator from the structure of the energy conservation reserve.

To determine the structure of the energy-saving reserve in the BOF process, one should compare the heat consumption and the technological operation costs in each technological operation:

$$C = \sum_{j=1}^{m} g_j \cdot e_j + \sum_{k=1}^{l} q_k \cdot e_k \quad (6)$$

where:

C - the cost of technological operation at each stage of production, kgce/t.

The results are presented in the **Table 7**.

The largest reserve of energy saving lies in the actual blast furnace production. The difference is 480 kgce due to the significant output of blast furnace gas, the irrevocable heat of blast furnace slag and represent almost 58 % of the energy saving reserve.

In addition, the shares of the reserve attributed to the production of concentrate, sinter, pellets and coke are inextricably linked with the BF production of pig iron and outside it is not necessary.

Then the total energy conservation reserve in the whole sinter-blast furnace complex reaches 74.16 %.

That is why the liquid-phase methods of non-BF and coke-free production of primary iron from ores are intensively investigated.

However, at present, in liquid-phase iron production processes COREX and ROMELT, which are based on coals without coking, the energy expenditure exceeds the BF by two or more times.

Table 7. **The structure of the energy conservation reserve in the production of BOF steel**

№	Semiproducts (s-p)	Costs	Heat Consumption	Difference	Difference
		kgce/t s-p	kgce/t s-p	kgce/t s-p	%
1	Concentrate	36.31	0.00	36.31	4.35
2	Agglomerate	82.89	44.20	38.69	4.64
3	Pellets	74.70	38.03	36.67	4.40
4	Coke	80.28	53.65	26.63	3.19
5	Cast iron	**767.78**	**287.40**	**480.38**	57.58
6	Steel	57.53	0.00	57.53	6.90
7	Hot rolled sheet	97.91	33.29	64.62	7.75
8	Cold rolled sheet	113.98	20.54	93.44	11.20
	Total:	1311.37	477.11	834.26	100.00

It is assumed, in the base of liquid-phase processes, that the reduction of iron oxides in the liquid phase is carried out by carbon or carbon monoxide, and that hydrogen is a very promising reducing agent [10, 11], but the question of the origin of carbon is not discussed, as is the influence of the ash part of coal on energy characteristics.

Meanwhile, it is known that at 1600° C the equilibrium compositions of CO-CO_2 reach only 16 % CO_2, while H_2-H_2O, respectively, 51 % H_2O, that is, under these conditions' hydrogen is a better reducing agent than CO.

Previous studies [10, 11] found that a carbon-hydrogen mixture (CHM) obtained by thermal decomposition of natural gas at temperatures above 1200 ºC can become a promising reducing agent for liquid-phase reduction of iron from ores.

A comparison of CHM and coals shows that the proportion of carbon in coals and CHM is close to 75 % by weight, and the remaining 25 % in coals is ash, and in SHS-hydrogen. This predetermines the decisive advantage of CHM as a reducing agent over coals, especially since CHM can be applied heated to 1200 – 1600 ºC and make a significant positive contribution to the heat balance of smelting.

As a result, the specific energy consumption for iron reduction when using CHM can be 1.5 - 2.7 times lower than when using coal.

Based on this, it was concluded that it is possible to develop a new GASMELT liquid-phase process with energy and resource-saving characteristics that can realize an energy-saving reserve in stage of primary iron production from ores [10, 11].

The ore concentration stage in some cases may include thermal operations. So, the siderite ores enrichment involves preliminary firing. Previous studies [12] established that in the firing-magnetic enrichment of siderite ores there is an energy-saving reserve, which makes it possible to increase the firing energy efficiency from 41.2 % to 77.3 %.

This is achieved by making fuller use of the high-temperature potential of natural gas combustion products, first - for generating electricity in a gas turbine installation, and then, in the low-temperature part under 650 °C – for burning siderite.

Moreover, the generated electricity is enough not only for the company's own needs, but also for power supply to the adjacent city.

The second part of the energy conservation reserve relates to steelmaking and steel casting, including a near-net-shape casting techniques. In this part, the relevance of using the high potential energy of liquid steel, including the latent heat of solidification, is emphasized [13].

Previous studies [14-16] found that it is possible (in principle) to use liquid metal agents for cooling and hardening steel, capable of removing all the heat of liquid steel with a high temperature potential of 780 – 1600 ºC, including the heat of steel hardening.

The greatest effect can be obtained when using the lead-bismuth alloy C-13 during direct casting of steel onto this denser coolant. At the same time, all the heat of the cast steel is used (including the latent heat of melting-hardening) and a strip of 3-5 mm thickness is obtained, that is, close to the final one.

It should also be noted that this method reduces the friction of the casting on the metal which is very high in the Continuous Casting Mold, and the speed of drawing the sheet on liquid C-13 layer can be increased, conceivably, to 1 - 10 m/s, i.e. 60-600 m/min.

The previous transition of metallurgical technology from casting to molds – to continuous casting was assessed as revolutionary. In this case, the transition from continuous casting to a profile with a thickness of 250 - 40 mm to continuous high-speed casting to a finished profile of 3-5 mm can have similar consequences. So, it becomes possible to reduce not only traditional water cooled continuous casting machines, but also groups of heating furnaces and all hot rolling equipment.

As for the heat removed from the hardening steel, at a maximum potential of more than 1500 °C it can be used in the BOF for melting steel scrap in an additional amount of up to 0.163 t [15]. This means the actual increase in the share of melted scrap in the BOF process from a fundamental limit of 20–25 % to 35-40 %, which is already comparable to the OHF process.

If the heat agent is heated not higher than 1500 ºC, then this heat can be used to generate electricity in a combined cycle with efficiency theoretically up to 60 %. This may already matter for the electric steelmaking process with its high specific energy consumption of 300 - 600 kW·h/t, since this fuel-free electricity generation from the heat of liquid steel can reach in the limit 233.4 kWh/t and to a large compensation of extent energy consumed from the network [15, 16].

Thus, the new results obtained solve some of the problems of the energy efficiency of ferrous metallurgy, posed in the previous works of other authors [2-7] and concerning the reduction of iron from ores, steel-making processes and the compensation of a significant amount of electricity in the electric steel-making process of steel production.

Conclusion

The primary diagnostics of the energy efficiency of integrated steel plant was carried out from the standpoint of the of intensive energy conservation methodology. The object of study was formed - a closed heat and technological complex of integrated steel plant in the range from iron ore deposits to the finished cold-rolled steel sheet. A comparison of the heat consumption and energy intensity of the products in the object showed that the energy efficiency of the existing complex for the production of steel from iron ores is about 40 %.

The complete energy conservation reserve and its structure are determined. An assessment of the complete intensive energy conservation reserve in the heat technology of the steel industry showed that it can reach 24 - 26 GJ/t of sheet. The structure of the complete intensive energy conservation reserve, including sinter-coke-BOF, and steel-casting-rolling parts, is determined.

The largest energy saving reserve is associated with the primary reduction of iron from ores. In this part, the reserve can be realized by transferring to liquid-phase reduction of iron from ores using promising energy carrier - hot products of thermal non-oxidative decomposition of natural gas (CHM).

In the steel casting-rolling part of the complex, the reserve can be realized by using the heat of liquid steel during its cooling and hardening. This can be done by using various liquid metal agents that do not interact with steel - for example: lead-bismuth alloys. Using the heat of liquid steel with a coolant potential of up to 1600 °C can be effectively applied for melting steel scrap for the BOF process and overcoming the existing limitation of the share of scrap in 25 %, which can make it possible to bring this share to 35–40 %, which is comparable to the OHF method.

The use of heat with a coolant potential of not higher than 1500 ºC can be effectively used to generate electricity for ESP process in an amount up to 233.4 kWh per ton of steel. Thus, a significant proportion of the energy consumption from the network to the ESP can be compensated, for by the balance, of the fuel-free generation of electricity from the heat of liquid steel. The planned directions for the implementation of energy saving reserves are possible in the transition to the new generation of engineering and technology, which fully meets the basic principles of the intensive energy saving methodology.

REFERENCES

1. Kartavtsev S. V., Neshporenko E.G., Matveev S. V. Primary diagnosis of energy efficiency in an integrated steel plant, based on intensive energy-saving methodology. Part 1. *CIS Iron and Steel Review*. 2021. Vol. 22. pp. 107-110.
2. Real Prospects for Energy Efficiency in the United States. National Academies Press, Washington, DC. 2010.
3. Worrell E., Blinde P., Neelis M., Blomen E., Masanet E. Energy Efficiency Improvement and Cost Saving Opportunities for the U.S. Iron and Steel Industry. Berkeley National Laboratory. October 2010. 160 p.
4. Stubbles J. Energy use in the U.S. Steel Industry: An Historical Perspective And Future Opportunities. Washington, DC. September 2000. 58 p.
5. Mohsen M. S., Akash B. A. Energy Analysis of the Steel Making Industry. *International Journal of Energy Research*. 1998. Vol. 22. pp. 1049 – 1054.
6. Deshmukh R., Bansode S., Kolgiri S., Hiremath R. Future Technologies for Energy-Efficient Iron and Steel Making Industry. *Imperial Journal of Interdisciplinary Research (IJIR)*. 2017. Vol. 3. Iss. 9.
7. Sultanguzin I. A., Isaev M. V., Kurzanov S. Yu. Optimizing The Production Of Coke, Coal Chemicals, And Steel On The Basis Of Environmental And Energy Criteria. *Metallurgist*. 2011. Vol. 54. No. 9–10.
8. Voskoboinikov V. G., Kudrin V. A., Yakushev A. M. General metallurgy. M.: Metallurgiya, 1985. 480 p.
9. Benyakovsky M. A. et al. Technology of rolling production: Reference book in 2 volumes.M.: Metallurgy, 1991. 862 p.
10. Kartavzev S. W. Iron ore smelting processes: GAZMELT way to efficiency. *METEC Conference on Science and Technology of Ironmaking. Proceedings. – Dusseldorf, 16 – 20 June*. 2003. pp. 60 – 61.
11. Kartavtsev S. V. Energy analysis of liquid-phase reduction of iron by natural gas. *Steel in Translation*. 2004. Vol. 34. No. 7. pp. 15-18.
12. Nikolaev A., Murzaderov A., Kartavtsev S., Neshporenko E., The Development of Energy-Efficient Scheme Roasting Siderite Ores Using a Gas Turbine Generation. *Proceedings of the 2016 IEEE North West Russia Section Young Researchers in Electrical and Electronic Engineering Conference (2016 ElConRusNW), February 2-3, 2016, St. Petersburg, Russia*. pp. 672 – 674.
13. De Beer J., Worrell E., Blok K. Future technologies for energy-efficient iron and steel making, *Annual Review of Energy Environment*. 1998. Vol. 23. No. 1. pp. 123–205.
14. Platonov I. V., Kartavtsev S. V. Possibilities of intense resource saving in electric furnace steelmaking. *Russian Metallurgy (Metally)*. 2013. No. 12. pp. 957–959.
15. Kartavtsev S., Nikolaev A., Neshporenko E., Matveev S., Dyomin Yu. Analysis of its Own Energy Independence Electric Steelmaking Process. *Proceedings of the 2016 IEEE North West Russia Section Young Researchers in Electrical and Electronic Engineering Conference (2016 ElConRusNW), February 2-3, 2016, St. Petersburg, Russia*. 2016. pp. 624 – 626.
16. Kartavtcev S., Matveev S., Neshporenko E. Heat-electrical regeneration way to intensive energy saving in an electric arc furnaces. (2018) *IOP Conference Series: Earth and Environmental Science*. 2018. Vol. 136. No. 1. 012003. DOI: 10.1088/1755-1315/136/1/012003.