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# Analysis of the possibilities of creating an autonomous energy supply system for metallurgical production using hydrogen technology and using the physical heat of metallurgical equipment

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# Аналіз можливостей створення автономної системи енергозабезпечення металургійного виробництва з використанням водневих технологій та фізичного тепла металургійного обладнання

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***Анотація.*** *Генерація ресурсів енергії автономної системи енергозабезпечення, їх раціональне за витратами та ефективне за результатами використання, сприяє забезпеченню сталого розвитку підприємства. В умовах її адаптованості до особливостей металургійного виробництва використання її потенціалу, незалежно від зовнішніх енергопостачальників, дозволить знизити собівартість продукції, мінімізувати втрати енергії та шкідливі викиди. Загалом - підвищити енергоефективність технологічних процесів і конкурентоспроможність металургійної галузі.* ***Мета дослідження****. Встановлення можливості реалізації в замкнутій, автономній та самодостатній системі енергозабезпечення, що адаптована до умов металургійного виробництва, інтеграції корисних енергетичних властивостей вихідного потенціалу електролізного водню та вторинного потенціалу фізичної теплоти, що є часткою енергії теплового балансу металургійних процесів, яка втрачається. Серед перспективних шляхів і ефективних способів забезпечення металургійних підприємств енергоресурсами, в умовах їх сучасного розвитку, стають: використання відновлюваних джерел електроенергії, інтеграція водневих технологій, залучення в основні процеси вторинних енергетичних ресурсів, застосування локальних енергокомплексів на основі більш повного використання потенціалу їх корисних властивостей. За результатами дослідження, реалізація замкнутої системи енергозабезпечення, як теплової інтеграції складових потенціалу водню, визначено, що вона може бути корисною в разі використання залишкової фізичної теплоти металургійного виробництва, що втрачається, в якості додаткового джерела електроенергії виробництва електролізного водню, але не як електрично самодостатній замкнутий цикл. Застосування в комплексі з металургійними процесами/агрегатами, де є значний потенціал для генерації залишкової фізичної теплоти газів та шлаків, є обмеженим, але важливим для зниження питомих витрат енергоресурсів на виробництво електролізного водню. Показано, що в замкнутій автономній системі забезпечення енергоресурсами при регенерації корисних властивостей потенціалу електролізного водню можуть виникати як позитивні так і негативні, за впливом на систему, ефекти синергії. Синергія в замкненій автономній системі енергозабезпечення може бути критично важливим фактором - джерелом додаткової ефективності, але лише за умови ефективного використання складових системи та грамотного технологічного контролю за ним.*

***Ключові слова:*** *ресурси енергії,замкнута система, електроліз, водень.*

***Abstract.*** *Generation of energy resources of an autonomous energy supply system, their rational in terms of costs and effective in terms of results of use, contributes to ensuring sustainable development of the enterprise. In the conditions of its adaptation to the peculiarities of metallurgical production, the use of its potential, regardless of external energy suppliers, will allow to reduce the cost of production, minimize energy losses and harmful emissions. In general, to increase the energy efficiency of technological processes and the competitiveness of the metallurgical industry. Purpose of the study. Establishing the possibility of implementing in a closed, autonomous and self-sufficient energy supply system, adapted to the conditions of metallurgical production, the integration of useful energy properties of the initial potential of electrolysis hydrogen and the secondary potential of physical heat, which is a part of the energy of the heat balance of metallurgical processes that is lost. Among the promising ways and effective methods of providing metallurgical enterprises with energy resources, in the conditions of their modern development, are: the use of renewable sources of electricity, the integration of hydrogen technologies, the involvement of secondary energy resources in the main processes, the use of local energy complexes based on a more complete use of the potential of their useful properties. According to the results of the study, the implementation of a closed energy supply system, as a thermal integration of the components of the hydrogen potential, it was determined that it can be useful in the case of using the residual physical heat of metallurgical production, which is lost, as an additional source of electricity for the production of electrolysis hydrogen, but not as an electrically self-sufficient closed cycle. Application in combination with metallurgical processes/units, where there is a significant potential for generating residual physical heat of gases and slags, is limited, but important for reducing the specific energy costs for the production of electrolysis hydrogen.It is shown that in a closed*

*autonomous energy supply system, during the regeneration of the useful properties of the electrolysis hydrogen potential, both positive and negative synergy effects may occur, in terms of their impact on the system. Synergy in a closed autonomous energy supply system can be a critically important factor - a source of additional efficiency, but only under the condition of effective use of the system components and competent technological control over it.*
***Keywords:*** *energy resources, closed system, electrolysis, hydrogen.*

**Introduction.** In the current conditions of development of metallurgical production, one of the key tasks is to increase its energy efficiency and reduce the negative impact on the environment. Traditional energy supply systems based on the use of fossil fuels are exhausting their potential, increasingly giving way to autonomous and innovative technologies. Among the main areas of autonomous energy supply of ferrous metallurgy processes, it is worth noting:

1. Use of renewable sources of electricity (solar and wind power plants, geothermal and bioenergy methods), integrated directly into the production infrastructure.
2. Introduction of hydrogen technologies both to replace traditional carbon technologies with direct iron reduction processes, and to accumulate and store energy in the form of "green hydrogen".
3. Application of secondary energy resource utilization systems (heat of by-gases and slags of blast furnace, ferroalloy and converter production) with subsequent use of physical and chemical energy in the main metallurgical processes and processing into electricity.
4. Local systems of energy complexes and microgrids, which provide flexible management of energy flow distribution and minimize their losses during transportation.
5. Integration of digital control systems (smart grid, monitoring and forecasting systems of consumption), which allow optimizing production loads and reducing specific energy consumption.

The implementation of these areas creates the prerequisites for the formation of innovative and environmentally balanced metallurgy, where autonomous energy sources are combined with the latest metal processing technologies. This opens up prospects for reducing the carbon footprint of production, increasing its competitiveness and transition to a "green" economy of the future.

**Analysis of autonomous closed systems for the production of energy resources and the likely results of their implementation at metallurgical enterprises.** In the current conditions of global challenges associated with the energy crisis and the need to reduce greenhouse gas emissions, metallurgical production requires fundamentally new approaches to energy supply. One of the priority areas may be the implementation of autonomous energy production and storage systems that can increase the efficiency of technological processes, reduce dependence on fossil resources and promote the transition to environmentally friendly metallurgy.

Among the most promising ways to provide enterprises with energy resources, we can single out: the use of renewable energy sources, the integration of hydrogen technologies, the utilization of secondary energy resources, the use of micro-macro networks and local energy complexes in combination with digital management systems. The integrated application of these solutions creates the prerequisites for the formation of a new model of ferrous metallurgy - energy-efficient, innovative and environmentally friendly.

The importance of the results of solving the identified problem is emphasized by the author [1]. Based on the analysis of the results of modern domestic and world research, taking into account the urgent need to apply innovative methods of energy accumulation, the author concluded that "the demand of our time is the development of scientifically sound tools for the practical implementation of decentralized heat supply based on alternative heat generators and hybrid means of accumulating energy resources for a wide range of sectors of the economy." At the current stage of development of scientific knowledge and technologies of "green metallurgy", the following negative challenges and its current unresolved problems should be recognized:

- high energy intensity of obtaining electrolytic hydrogen - from 50 to 55 kWh per 1 kg of hydrogen;
- discrepancy between the price of "green hydrogen", which is 2–3 times higher than "gray" hydrogen or coke, and the needs for a stable and cheap source of "green" electricity;
- lack of reliable and effective technological schemes and devices to ensure the safe supply of pure hydrogen to the furnace or other thermal unit.

Therefore, it is advisable to remember that the use of electrolysis in industrial conditions without the use of cheap sources of electricity will not become systemic, and hydrogen can be obtained less expensively from fossil fuels, natural gas, for example.

Regarding the sources of chemical energy, which is necessary for the implementation of modern metallurgical processes, the technologies of which are based on the reduction of iron from enriched iron ore concentrates, which have a physicochemical orientation. Hydrogen is one of the most promising energy resources, the useful properties of the initial potential of which can provide, subject to a significant reduction in the price of its production, metallurgical production with chemical (reducing agent), thermal (fuel) energy. Thus, the recycling of the components of the initial potential of hydrogen is able to provide energy for the successful implementation of the main stages of the end-to-end technology of steel production by creating thermodynamic conditions for the implementation of externally controlled physicochemical transformations in a given direction with the expected speed and final result.

One of the directions of rational use of the useful properties of the initial potential of hydrogen and the secondary potential of physical heat, which is a part of the energy of the heat balance of melting metals and alloys, which is lost for objective reasons, in our opinion, is their combination (integration) in a centralized, closed, autonomous, self-sufficient and adapted to the requirements and features of production system. It is obviously capable of ensuring its stability when implementing the following scheme of energy generation: “residual physical heat lost during the implementation of relevant metallurgical processes → electrical energy for powering electrolyzers or other devices → hydrogen”. In more detail, the mechanism and features of the implementation of the proposed scheme are expedient to determine as follows. The residual physical heat that is lost is accumulated in the products of the relevant processes: gases, slag, lining and metal housings of thermal units. Existing methods of its use allow generating the physical heat of gases and slag into steam, and subsequently obtaining electricity. The unused portion that is lost remains that which accumulates in the metal housings of thermal units.

**Justification of a system of autonomous, self-sufficient provision of metallurgical production with environmentally friendly energy resources.**

The system can be implemented through a system of mutual connections and influence of energy resources that are of artificial origin or are naturally renewable and capable of regeneration due to controlled external influence [2].

A structured scheme of autonomous energy supply of metallurgical production in the form of blocks and a logical chain “generation → recycling → effects → result” is expedient to present in the following way:

1. Generation of energy resources:
- use of hydrogen as an energy carrier (electrolysis, renewable processes);
- involvement of renewable energy sources (solar, wind, bioenergy);
- production of electricity by local installations (gas turbines, fuel cells);

2. Recycling of energy resources:
- utilization of physical heat of blast furnace, coke oven and converter gases;
- use of physical heat and chemical energy of molten slags;
- reuse of by-products of thermal processes (recycling of waste of technogenic origin).

3. Effects of implementation:
- reduction of dependence on external energy suppliers;
- rationalization of energy and fuel costs;
- reduction of $CO_2$ emissions and other pollutants;
- optimization of the cost of metal products.

4. Result of implementation:
- stable, safe and uninterrupted operation of metallurgical units;
- increase in energy efficiency of production in general;
- environmental sustainability and innovativeness of the metallurgical industry;
- increase in the competitiveness of the enterprise in the world market.

The externally controlled interaction of blocks, a logically defined chain, determines the capabilities of the autonomous supply system and the level of its self-sufficiency. In autonomous closed energy supply systems of metallurgical production, synergy effects of both positive and potentially negative impact on the system may arise

Table 1 Synergy effects in closed autonomous systems for energy generation and recirculation

| No. | Type of synergy effect | Impact on the system | Consequence for the functioning of metallurgical production |
|---|---|---|---|
| 1 | Positive – energy isolation | Balance of energy generation and recycling | Reduced dependence on external suppliers, stable operation of units |
| 2 | Positive – increased efficiency | Integrated use of hydrogen, secondary gases, heat of waste streams | Increase in the efficiency of energy components, reduction of production costs |
| 3 | Positive – environmental effect | Reduction of $CO_2$ and harmful substances emissions into the environment | Increasing environmental sustainability and compliance with international standards |
| 4 | Positive – reliability | Energy backup thanks to the use of combined sources | Continuity and stability of technological processes even at peak loads |
| 5 | Negative – difficulty in driving | The need for multi-thread integration | High requirements for automation and digital monitoring |
| 6 | Negative – uneven formation of resources | Cyclical nature of the emergence of secondary energy resources | Possible imbalances in supply and energy losses in the absence of storage systems |
| 7 | Negative – technological risks | Explosiveness and specificity of the influence of hydrogen properties | Increased requirements for safety, workers and equipment |
| 8 | Negative – capital intensity | Significant investment costs for implementation | Slow scaling of the system without state support, grants, investments |

The impact of effects on the functioning of the system is realized:

- with a reasonable balance, the positive effects of synergy dominate, the system becomes more stable, more cost-effective, and the level of environmental cleanliness increases;

- if negative factors are not taken into account, energy imbalance, overloading of the system may occur, which will become a source of accident risks and a reason for a decrease in its energy efficiency.

The introduction of intelligent control systems (digital modeling, IIoT, big data analytics [3]) will obviously allow to coordinate all flows of energy source regeneration and minimize the occurrence of negative synergistic effects. That is, synergy in a closed autonomous energy supply system can be a critically important factor - a source of additional efficiency, but only if competent technological control is carried out.

It should be noted that the level of efficiency of the autonomous power supply system is significantly influenced by the state of the fuel and resource base of traditionally used materials, the potential of which is exhaustive [4].

The idea of "closing" the life cycle of the beneficial properties of hydrogen by installing thermoelectricity on hot cases, at first glance, is quite logical as a first assumption. But if we take into account industrial temperatures and the real capabilities of serial TEGs (thermoelectric generators), it turns out that the electricity (hereinafter referred to as electricity) that a certain number of TEGs can generate will not be enough, to make the cycle self-sufficient, ultra-large heat flows and active areas are needed. Therefore, the closed circuit "electrolysis → $H_2$ → back into electricity" is likely to require the use of an additional source of electricity to power the electrolyzers.

Thus, the efficiency of industrial TEGs based on $Bi_2Te_3$/PbTe today is mostly ~ 5–8%. (in the conditions of laboratory experiments, in the serial industry, this figure is lower). Typical specific power/efficiency of TEGs at ΔT ~150–200 °C, according to data [5], are units to tens of watts per module with dimensions of 40×40 mm, which means the need to have extra-large areas and massive heat exchangers/radiators.

To determine the system position based on indisputable facts, it is necessary to establish the reality of the implementation of the scheme with the use of residual heat, which "seems" free. Calculations of the higher calorific value of hydrogen, which is determined from the enthalpy of liquid water formation under standard conditions, i.e. includes both the heat of reaction and the heat of condensation of water vapor, show that its value is 39.4 kWh/kg.

The reverse conversion of $H_2$→electricity by combustion of hydrogen in a fuel cell gives according to calculations 50-60% of LHV, i.e. ~16-20 kWh/kg; gas turbine/internal combustion engine — even lower (~35–45% → ~12–15 kWh/kg).

It turns out that, even in the ideal case of SOEC with "free" heat, to implement the direct stage of the hydrogen life cycle "electricity → electrolysis" it is necessary to use ~28–30 kWh/kg, and when implementing the reverse stage, the electricity that can create hydrogen combustion ("hydrogen combustion → electricity") is only ~16–20 kWh/kg for (PEM-FC) or ~12–15 kWh/kg when using a turbine. And to obtain 1 kWh of electricity, it is necessary to use ~7–10 kWh of heat. Against the background of the needs of ~28–30 kWh/kg of $H_2$, these are huge heat flows. That is, the electrical balance of the closed circuit under study will always be in the negative. "Free" heat helps to reduce the electrolyzer's electricity consumption, but does not make the cycle self-sufficient in electricity.

However, the scheme of regeneration of the initial useful properties of the potential of hydrogen as an important energy resource for metallurgical production can be useful for: reducing the specific electricity consumption of hydrogen in high-temperature electrolyzers (SOEC + waste physical heat, which has a secondary origin); improving the overall heat balance of the relevant workshops due to: heating water, steam production, recovery of secondary energy of exhaust gases - products of metallurgical processes, preliminary drying of the components of the initial charge); using $H_2$ as a reducing agent in DRI/DRH - all these are factors that contribute to obtaining the greatest process gain, for example, in the kinetics of metallurgical reactions, in ecology by reducing $CO_2$ emissions.

If measured by the consumption of electrical energy (it is she who feeds the electrolyzer), then, even with "free" heat, the electrolyzer consumes more kWh_ per 1 kg of $H_2$ than can be returned from this kilogram of hydrogen in the form of kWh when it is burned.

Therefore, the idea of a closed energy supply system should be defined as useful as thermal integration, which will reduce electricity consumption for hydrogen production, but not as an electrically self-sufficient closed cycle. And its application in combination with metallurgical processes/units, where there is a significant potential for generating residual physical heat of gases and slags, is limited.

For a well-founded determination of the advantages and disadvantages of a closed energy consumption system, it is advisable to determine the technical characteristics of its components, namely high-temperature electrolyzers, thermoelectric generators, regarding the compatibility of their capabilities, as elements of the system for regenerating their properties.

Thermoelectric generators (TEG) are installed on heat-generating areas of metallurgical equipment, in particular on the external surfaces of furnaces, converters or heat-conducting channels through which hot exhaust gases are discharged. The hot side of thermoelectric modules is placed on the surface of their housings, in contact with it, and the cold side is cooled using water or air cooling.

To determine the effectiveness of the use of existing types of TEGs, let's turn to actual data and analyze their real capabilities:

- The efficiency of industrial TEGs based on $Bi_2Te_3$/PbTe today is mostly ~5–8% (in the best cases of laboratory materials - higher, but this is not a serial industry) [5];

- A high-temperature SOEC electrolyzer with heat supply gives ≈ 36–40 kWh_electricity/kg $H_2$;

- The typical specific power/efficiency of TEGs at ΔT ~150–200°C is units to tens of watts per 40×40 mm module according to their technical data.

In a system implementation, this means large areas and massive heat exchangers/radiators.

It is advisable to determine the parameters of technical support for the use of physical heat accumulated in the metal housings of thermal units, in conditions of practically no traffic, unlike exhaust gases and slags - waste from metal smelting.

First, let's determine the number and area required to accommodate the appropriate number of TEGs, which will provide electricity to the high-temperature electrolyzer, which in turn - hydrogen in an amount sufficient to produce 10 tons of iron per day by its direct reduction.

Secondly, when calculating the number of thermoelectric generators required to produce 10 tons of iron per day, the following initial data were determined and the following assumptions were made:

- raw material - hematite $Fe_2O_3$; main reaction: $Fe_2O_3 + 3 H_2 \rightarrow 2 Fe + 3 H_2O$;

- 625 TEG modules can be placed on 1 m² of the surface of the heated unit housing;

- linear approximation of module performance $П \propto ΔT$;

- cold side Tcold = 30 °C;

- consider options with Thot = 200, 300, 400, 500 °C.

- electrolyzer — high-temperature SOEC, which consumes 36 kWh/kg $H_2$ [6].

Для розрахунку показників, що приведені в табл. 2, використані дані з [6], it also gives the initial factors that affect the calculation results: the cold side of the module is 30 °C, the surface temperatures of the industrial unit housing (hot side of the modules) in °C are 200, 300, 400 and 500. Also, for these conditions, the corresponding values of the electric power of the TEG modules (SOEC) are determined. Data on the influence of the characteristic temperatures and technical capabilities of thermal electric generators (TEG) on the electric power are summarized in the following table. 2.

Table 2 – Influence of the characteristic temperatures and technical capabilities of thermal electric generators (TEG) on the electric power

| № | $T_{hot}$ (°C) | ΔT (°C) | P according to option A , W/module | P according to option B, W/module |
|---|---|---|---|---|
| 1 | 200.0 | 170.0 | 3.107 | 5.667 |
| 2 | 300.0 | 270.0 | 4.935 | 9.0 |
| 3 | 400.0 | 370.0 | 6.763 | 12.333 |
| 4 | 500.0 | 470.0 | 8.591 | 15.667 |

The analysis of the data given in [7] allows us to determine the following. A target electrolyzer of 100 kg $H_2$/day (≈ 4.17 kg/h) when using a TEG (SOEC) delivering 40 kWh/kg requires ≈167 kW of electricity continuously. If the efficiency of TAGS is 5–8% [8], to achieve this indicator, it is necessary to create a heat flux of about 167 kW/0.08 ≈ 2.1 MW (for 8%) or 167/0.05 ≈ 3.3 MW (for 5%). That is, in order to remove 2÷3 MW from the heated surfaces of metallurgical units and, at the same time, it is necessary to stably keep the other side of the TEG cool and fulfill the condition ΔT = const. This is already a different level – for example, the level of a much higher volume of heat recovery of exhaust heated gases.

If we take an optimistic commercial figure of ~10 W from a 40×40 mm (16 cm²) module and a high ΔT value, then the need to obtain **167000** W requires ≈16700 modules, i.e. ~267 m² of active area for the placement of TAGs. Even if the electrolysis is partially or completely "powered" by the TEG, the reverse conversion of $H_2$→electricity from the use of a fuel cell to burn a fraction of hydrogen (the efficiency of PEM is ~55%) will yield less kWh_of electricity than will be spent on electrolysis. Below are the main results of calculating the amount of hydrogen for the production of 10 tons of Fe, explanations and practical conclusions are made regarding the probability of implementing the process in a closed system.

1. Calculation by stoichiometry of the reaction $Fe_2O_3 \rightarrow Fe$ allows you to determine the mass of $H_2$ required for the production of 10 tons of iron by the method of its direct reduction: ≈ 541.499 kg $H_2$ (54.15 kg $H_2$ per 1 ton of Fe) or 0.05415 kg $H_2$ per 1 kg Fe).

2. Electricity required to produce a given amount of hydrogen when using a high-temperature SOEC electrolyzer:

- energy for electrolysis is: 541.499 kg × 36 kWh/kg≈ 19494 kWh (≈ 19.5 MWh per 10 t Fe);

- if you produce 10 tons of Fe evenly in 24 hours, you need to provide a continuous power of ≈ 812.25 kW;

- for the production of 1 ton of Fe, it is necessary to spend ≈ 81.23 kW of electricity.

3. The amount of electricity that 1m2 of the heated surface of the metal body of the melting unit can provide, on which 625 TEG modules of 40×40 mm can be placed (cold side temperature 30 °C) and calculation of the total area for their placement:

The calculations were carried out for the performance of one TEG module, respectively, in W/module

3.29 – according to the conservative option (A) and 10.0 – according to the standard option (B).

For Thot = 200/300/400/500 °C, ΔT is, respectively, 170/270/370/470 °C):

According to option A (3.29 W/module), Thot = 200°C and ΔT=170°C:

- electric power - P (kW/m²) is approximately 1.947; 3,245; 4,543; 5.841. Change interval (1.95 ÷ 5.84 kW/m2).

- the required area of TEG (m²), which will provide 812.25 kW: ≈ 416.9 m² for 200°C; 250.4 m² for 300°C; 178.9 m² for 400°C and 139.2 m² for 500°C;

According to option B (10 W/module), Thot = 300°C and ΔT=270°C:

- electrical power P (kW/m²) is approximately 3.125; 5,208; 7.292 and 9.375 - (3.13 ÷ 9.38 kW/m²);

- required TEG area (m²) for 812.25 kW: ≈ 259.9 m² for 200°C; 156.1 m² for 300°C; 111.5 m² for 400°C and 86.6 m² for 500°C.

The results of the study show that the installation of TEGs in the fuel generating areas of metallurgical units (metal casings of blast furnaces, oxygen converters, mixers and other thermal units and equipment) is a rather important technical solution from the point of view of the use of energy from secondary sources. Its introduction will ensure an increase in the level of energy efficiency of a metallurgical enterprise with integrated hydrogen production, which is used at one of the important stages of the end-to-end technology of steel production - direct reduction of iron.

Such a solution will allow you to use thermal energy, which only heats the air around, is practically free of charge and allows you to "reduce energy consumption from external sources and does not require significant costs.

4. Interpretation of calculated indicators and practical conclusions

The amount of $H_2$ to produce 10 tons of Fe is ≈ 541.5 kg, which gives an idea of its scale (hundreds of kilograms of $H_2$ per day).

The need to have a constant, continuously stable electrical power of TEGs at the level of ≈ 0.81 MW. To power the SOEC type electrolyzer, exclusively by heating the TEG from the housings of thermal units, it is necessary to have hundreds of square meters of their surface to accommodate the TEG modules.

Areas of hundreds of m² are realistic, but not trivial, because it is necessary to solve the issues of installation costs, accessibility of the surface of the enclosures, the availability of area for the placement of TAGS at the appropriate ΔT values, the conditions of heat transfer and cooling of the "cold side" of the modules, mechanical resistance, the cost of the modules, their moral and physical wear and maintenance of the modules, which is also important.

Burning a certain fraction of hydrogen, if it is excess for the needs of iron recovery, and creating a reserve seems to be a technically correct solution. But using the capacities of TEGs of modern modifications, from the point of view of economic sense, for burning hydrogen without a significant reduction in the price of its production of hydrogen using high-temperature electrolyzers, is not an effective solution.

An important fact that must be taken into account when solving similar problems is that a completely "closed" regeneration scheme, where the heat of the heated bodies of the melting units → electricity → electrolysis $H_2$ → $Fe_2O_3$ recovery → combustion of a fraction of $H_2$ → heat → electricity to power the electrolyzers → $H_2$, even theoretically, cannot exist due to energy losses, according to the 2nd law of thermodynamics (heat of combustion of $H_2$ < electricity consumption for electrolysis). But it is advisable to implement the regeneration system links by utilizing the energy of secondary sources of steelmaking production for electric feeding and heating of electrolyzers (especially of the SOEC type).

According to the data given in [5,9], even when using SOEC, the electricity consumption per 1 kg of H2 remains higher than its electrical value during the reverse transformation through the combustion of H2 (heat → electricity → electrolysis hydrogen), and the switching losses at each step of the physicochemical transformations make complete "regeneration" impossible.

Summing up the interim conclusion of the study, it is necessary to determine that parts of the closed chain of transformations of the closed circuit as the subject of the study have already been partially implemented according to the scheme WHP→steam/electricity→SOEC; $H_2$-DRI; utilization of waste/heat of liquid steel for hydrogen production). But a closed life cycle of $H_2$ regeneration in industrial production cannot exist due to fundamental losses, which are objective.

It is advisable to comment on the regenerative scheme of using the properties of the components of the WHP→steam/electricity→SOEC scheme, having determined the functional aspects of their transformation.

1. WHP (Waste Heat Potential). The source is secondary energy resources, in particular the heat of gases - products of metallurgical processes, the heat of cooling of metallurgical units and other thermal units. Their properties are realized as low and medium potential energy, which is traditionally difficult to utilize.

2. The intermediate stage of transformation of secondary industrial heat into steam or electricity. It is realized through waste heat recovery boilers or ORC systems, where the waste heat is converted into technical steam or electricity. Physicochemical processes at this stage are indirect - heat converts the working fluid ($H_2O$, organic liquids) into another energy state.

An important point of transformation is that the concentration and improvement of energy quality occurs according to the scheme low-potential heat → electricity or steam under pressure.

3. SOEC (Solid Oxide Electrolysis Cell). The obtained electricity and steam are used to implement the electrolysis of water at high temperatures (700–850

°C). The following processes are implemented in this process:

- electricity provides electrochemical splitting of the $H_2O$ molecule;
- steam reduces the need for electrical energy (part of the energy is supplied in the form of heat).

At the output after the regeneration-transformation cycle of the initial properties of the system elements by separation, individual streams of high-purity hydrogen ($H_2$) + oxygen ($O_2$) are obtained.

The features that determine the functional aspects of regeneration are:

4. Functional-regenerative aspect of regeneration. The system of physicochemical transformations works as a closed loop of transformation of its initial elements according to the scheme: secondary physical heat → higher quality energy carriers → chemical energy carrier ($H_2$);

The complex of physicochemical transformations is carried out by:

- transition of heat into phase changes (evaporation/condensation);
- electrochemical decomposition of water into hydrogen and oxygen;
- regeneration of the thermal part by using high-temperature waste in SOEC for electricity.

5. The main features as characteristic features of the processes in the system include:

- regenerativity, as an important feature of the system, is characterized by the involvement of waste streams and their "refueling" in a new energy exchange cycle;
- the exergy effect is realized through an increase in the share of useful energy, the source of which is secondary waste energy;
- system flexibility - hydrogen, as a result of the implementation of processes in the system, can be reused in production (metallurgy, as a fuel element of the system and energy storage).

Thus, the WHP→steam/electricity→SOEC scheme is an example of cascade energy transformation, where low-quality secondary physical heat is brought into the form of a high-quality energy resource — useful components of hydrogen through a series of successive physical and chemical transformations that create a micro-macrosystem. The main functional purpose of which is to be used as a "green" reducing agent in the processes of direct reduction of iron ($H_2$-DRI), with the ability to accumulate hydrogen if necessary.

In real conditions, the efficiency of electrolysis is approximately 50-60%. This means that only part of the consumed electricity is converted into a useful chemical component of its potential, the other part is lost in the form of physical heat. Therefore, it is advisable to use the "free" physical, residual heat as a source of secondary energy, which will reduce electricity consumption for the production of 1 kg of $H_2$, bringing closer to the implementation of the idea of making this cycle closed and energetically self-sufficient. And a more realistic direction of improving the energy efficiency of metallurgical production can be the deepest possible thermal integration of high-temperature electrolysis with electricity from TEGs, which will use the thermal energy lost during the implementation of metallurgical processes, with further optimization of the share of $H_2$ between recovery, which is the highest priority, and incineration as an additional source of the thermal process of the corresponding process/production.

Regarding the prospects for the use of high-temperature electrolysis. There are many combinations of performance, efficiency, service life and cost indicators, which, according to [6], allow you to achieve the main goal of hydrogen production at a low cost of $ 2 per 1 kg of H2 by 2026 and $ 1 per 1 kg of H2 by 2031. The combinations of objectives given by the authors were developed with the participation of industry experts and national laboratories; They can be considered a reference point for technology developers.

Thus, the idea of a closed power supply system must be determined to be useful in terms of integrating the initial properties of the elements. The result of their transformation is the emergence of optimal schemes for the distribution of the components of the energy of the system. This will reduce electricity consumption for hydrogen production, but not as an electrically self-sufficient closed loop. Therefore, the application in combination with metallurgical processes/aggregates, where there is a significant potential for generating residual physical heat of gases and slags, is limited.

**Conclusions.** The idea of "closing" the regeneration cycle due to the production of thermoelectricity on hot cases of metallurgical equipment, considered and analyzed for the reality of introduction, is quite logical as the first assumption. But if we take into account the potential of their physical heat as a source of electricity and the technical capabilities of TEGs (thermoelectric generators), it turns out that the electrical energy they are able to generate will not be enough to make the cycle closed and self-sufficient in terms of the potential of the energy used and restored again in the reverse way. This requires extremely large heat flows and areas, but the cycle of "electrolysis → $H_2$ → back to electricity" will always be in the red, due to the significant electricity costs for electrolysis, which requires additional use of electricity from external sources. Each repeated cycle will add losses due to incomplete conversion, losses on heat transfer and power supply of auxiliary equipment and compression, hydrogen purification.

It is advisable to use the results of the study in solving similar problems in the creation of regeneration schemes based on the combination of secondary sources of physical heat with the possibilities of obtaining electrical energy from it - the integration of solid oxygen hydrogen electrolyzers into the infrastructure of steelmaking.

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