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«GREEN» RESTORATION OF THE STEEL INDUSTRY OF UKRAINE

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Abstract. *The article addresses current issues regarding the restoration of Ukraine's steel industry in the context of post-war reconstruction, considering environmental factors. An analysis of the current state of steel production in Ukraine was conducted, particularly focusing on structural characteristics caused by extensive destruction and obsolete technologies. Promising avenues for the modernization of the industry were outlined, including the implementation of eco-friendly technologies, such as production via the DRI-EAF technological route using «green» hydrogen. Special attention is given to the financial and organizational challenges that need to be addressed to attract investment and ensure the industry's competitiveness in the global market.*

Key words: *«green» steel, modernization, decarbonization, «green» recovery, hydrogen technologies.*

Introduction.

The metallurgical complex of Ukraine remains a strategic sector of the economy despite significant challenges in recent years. According to estimates by the GMK Center, this sector accounted for 12% of Ukraine's GDP in 2018, contributing 26% of total goods exports [1]. However, due to the destruction caused by Russian aggression against Ukraine, the loss of control over production capacities, logistical constraints, energy shortages and price increases, and a lack of workforce, the share of the metallurgical complex in Ukraine's GDP decreased to 6% in 2023. Nevertheless, this remains a significant indicator for the economy [2]. At the same time, the global trend toward «greening» the economy, Ukraine's commitments to reducing greenhouse gas emissions under the Paris Agreement, and the introduction of the Carbon Border Adjustment Mechanism (CBAM) pose new challenges for steel producers. These factors necessitate substantial investments in production greening and the modernization of manufacturing processes – not only to achieve sustainable development goals but also to maintain competitiveness in global markets and ensure the successful post-war recovery of the sector.

Purpose of the article.

Analyze the structure of steel production in Ukraine and outline the key directions

for the «green» post-war recovery of the industry.

Analysis of research and publications.

The issue of «greening» steel production has been the focus of numerous studies by both domestic and international researchers.

Smirnov et al. (2023), in their monograph «Steel of Ukraine: Recovery and Innovations» provide a comprehensive analysis of the state of Ukrainian metallurgy, focusing on the efficiency of its energy and environmental parameters compared to leading developed countries. They examine key structural and technological solutions for modernizing existing capacities and envision the development of Ukraine's steel industry through electric steelmaking processes within mini-mills, incorporating hydrogen and electrolysis technologies [3].

Saha (2021) proposes a comprehensive approach to decarbonizing the steel industry, addressing both technological and policy aspects. Specifically, the author advocates for the adoption of advanced technologies, such as hydrogen-based DRI-EAF, which can significantly reduce CO_2 emissions and enhance operational efficiency. On the policy front, the recommendations include the gradual introduction of a carbon emissions tax and the establishment of a modernization fund aimed at supporting investments through grant financing mechanisms [4].

Melnyk (2022) highlights the efforts of international organizations, such as the UN and the EU, in combating climate change and underscores the importance of decarbonizing the metallurgical industry. Particular emphasis is placed on the transition to renewable energy sources and hydrogen technologies being adopted by leading steel producers (SSAB, ThyssenKrupp, ArcelorMittal). The study notes the promising potential of hydrogen technologies in direct reduced iron (DRI) production while also raising concerns about the risks associated with hydrogen use, which require further analysis [5].

Somers (2022) describes the current challenges and strategies that could position the EU as a leader in creating markets for environmentally friendly steel. The study also analyzes pilot projects and investments in breakthrough technologies, which require substantial capital investments [6].

The main material.

In light of climate change driven by anthropogenic greenhouse gas emissions, the issue of reducing such emissions and mitigating human impact on the environment has become existential. For the steel industry, this challenge manifests as the need for decarbonization.

However, is the term «decarbonization» appropriate when applied to reducing greenhouse gas emissions in steel production? Clearly, carbon is an integral component of steel, with its mass fraction ranging from 0,02% to 2,14%. The carbon content determines key physical and mechanical properties of steel, such as strength and ductility. Thus, the complete elimination of carbon from metallurgical processes is technically impossible.

The author suggests that terms like «modernization of the metallurgical industry» or «green steel» are more appropriate. In international practice, the term «green» typically refers to technologies that significantly reduce the negative environmental impact. However, this raises further questions: What qualifies steel as «green»? Which technologies hold the greatest promise? What steps need to be taken in the short, medium, and long term to achieve maximum emission reductions and minimize human impact on climate change? But the central question remains – how can Ukraine rebuild its steel industry after the war?

Figure 1 illustrates the structure of steel production in Ukraine from 2010 to 2023. The data analysis highlights the significant share of open-hearth steelmaking, which, despite its historical significance, is both technically and morally obsolete. This method is characterized by extremely low energy efficiency compared to modern approaches such as electric arc furnace (EAF) and basic oxygen furnace (BOF) production.

Since 2022, Ukraine's steel production has decreased by 70%, dropping from 21,3 million tons to 6,3 million tons. The primary causes of this decline include the loss of control over and physical destruction of key industrial enterprises, notably the Mariupol metallurgical plants «Azovstal Iron and Steel Works» and «Ilyich Iron and Steel Works» as a result of the full-scale military aggression by the Russian Federation against Ukraine.

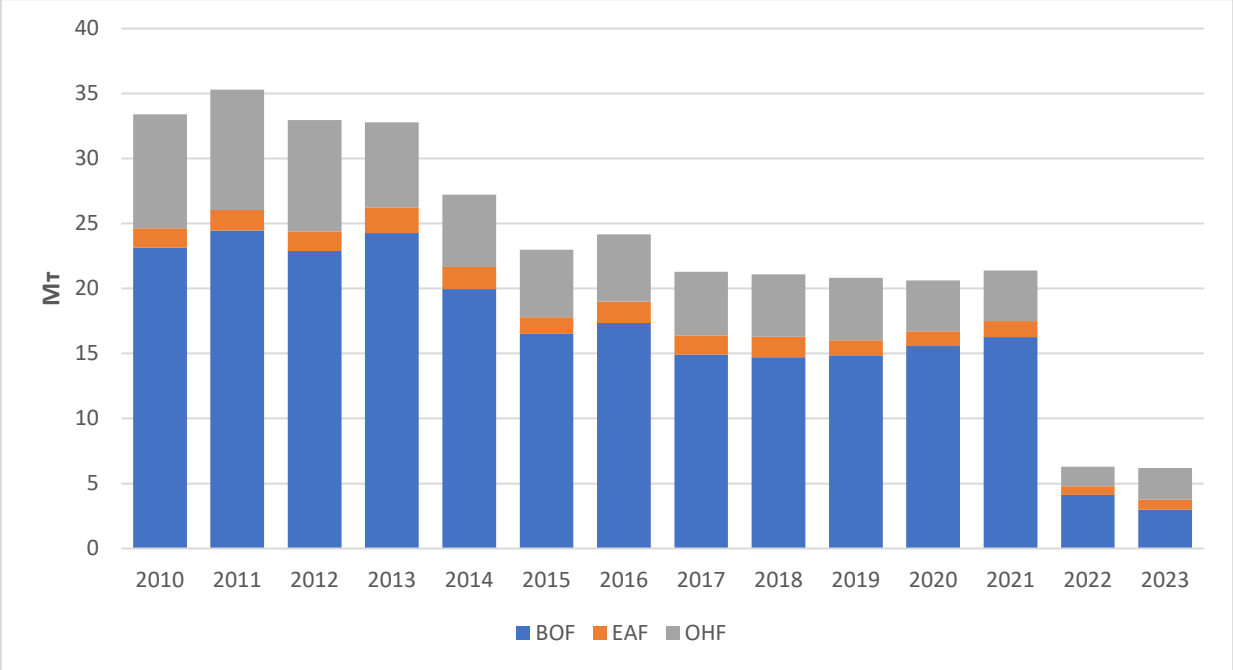

Figure 1 – Structure of steelmaking in Ukraine, 2010-2023

Source: [7]

As of 2023, the share of steel production using electric arc furnaces (EAF), one of the key examples of «green» technologies in Ukraine's metallurgical sector, accounted for only about 12,3%. These production facilities include enterprises such as PJSC «Interpipe Steel», PJSC «Dniprospetsstal», PJSC «NKMZ», and others.

However, a significant portion of steel production in Ukraine still relies on obsolete technologies that urgently require modernization or complete decommissioning. Open-hearth furnaces, which were relevant in the first half of the 20th century, continue to be used at PJSC «Zaporizhstal», which accounted for approximately 40% of the total steel production in 2023.

Although basic oxygen converters are a more modern alternative compared to open-hearth furnaces, their technological process also involves the use of coal as a reducing agent, making this method environmentally unsustainable and carbon-intensive. Consequently, this technological route has limited long-term potential.

Currently, about 48% of Ukraine’s steel is produced using basic oxygen converters, with key facilities including PJSC «ArcelorMittal Kryvyi Rih», PJSC «Kamet-Steel», and PJSC «Dnipro Metallurgical Plant» (DCH).

This situation highlights both significant challenges and considerable potential for modernizing Ukraine's steel industry, particularly by increasing the share of environmentally friendly technologies and upgrading existing facilities.

Currently, promising and carbon-neutral technologies include direct reduced iron (DRI) production using «green» hydrogen combined with electric arc furnaces (EAF), as well as iron electrolysis. These innovative approaches are geared toward medium- and long-term implementation due to their technological complexity and the need to develop the necessary infrastructure.

As of September 2021, 18 projects related to the construction of hydrogen-based DRI plants were underway in EU countries. These projects are at various stages of development, ranging from early announcements to the operation of pilot installations [6].

One of the most advanced projects is Hybrit, implemented through a partnership between steel producer SSAB, mining company LKAB, and energy company Vattenfall in Sweden. The project aims to decarbonize the entire steel value chain, including iron ore mining, and involves the construction of a pilot plant for hydrogen storage. According to Hybrit, the steel production process using this technology generates minimal carbon dioxide emissions, primarily due to the use of graphite electrodes and the addition of fluxes in the electric arc furnace. The total emissions amount to less than 0,05 tons of CO_2 equivalent per ton of steel, which is significantly lower than traditional blast furnace production, where this figure reaches approximately 2,2 tons of CO_2 equivalent per ton of steel [8].

In the context of Ukraine, investing in the construction of plants utilizing the DRI-EAF technological route is economically justified. Ukraine holds 18% of the world's explored iron ore reserves, and in terms of iron content, its share accounts for 10,5-11% of global reserves, placing it among the top five countries [9]. Additionally, the country has favorable geographic conditions for developing «green» hydrogen production due to optimal areas for generating renewable energy. This creates opportunities for integrating hydrogen into the national gas transmission system and exporting it to European countries. However, the implementation of such projects,

particularly the development of hydrogen energy, requires substantial financial investment.

Iron electrolysis is a promising technology for producing «green» steel, especially when powered by renewable energy. This method has the potential to significantly reduce carbon emissions by eliminating the need for fossil fuels. However, iron electrolysis technology is currently in the development stage, and its widespread adoption requires further research and refinement. In 2023, ArcelorMittal announced plans to construct Volteron, the world's first plant to utilize low-temperature iron electrolysis technology, with the goal of commencing full-scale production by 2027 [10].

At present, the most straightforward and achievable step toward reducing greenhouse gas emissions in the metallurgical sector is investing in and constructing electrometallurgical facilities that utilize electric arc furnaces (EAF) or induction furnaces, with steel scrap as the primary raw material. According to WorldSteel data for 2023, 71,1% of global steel production relies on the blast furnace-basic oxygen furnace (BF–BOF) route, while electric steelmaking accounts for 28,6%. This indicates significant potential for expanding electric steelmaking technologies, which, when powered by renewable energy, support sustainable development goals and offer a more environmentally friendly alternative.

Ukraine's steel production facilities that rely on open-hearth furnaces are obsolete and uncompetitive in terms of both energy efficiency and environmental standards, necessitating their gradual decommissioning. In contrast, facilities utilizing basic oxygen converters can remain operational, provided that technologies for carbon capture, utilization, and storage (CCUS) are implemented. This technology involves not only capturing CO_2 from emission sources and transporting it to storage sites for isolation from the atmosphere but also the potential use of captured CO_2, particularly in the chemical industry.

According to data from the International Energy Agency, the cost of implementing CCUS in steel production is estimated at $40–100 per ton of CO_2 equivalent. WorldSteel reports that in 2023, average CO_2 emissions per ton of steel

produced using basic oxygen converters were 2,33 t/t. This implies that applying CCUS could increase the cost of steel production by $93–233 per ton. However, it is anticipated that with market development, technological improvements, economies of scale, and accumulated experience in the construction and operation of CCUS facilities, the costs of this technology will gradually decline [11].

The successful modernization of Ukraine's steel industry requires significant financial investments that cannot be fully provided by national producers alone. Achieving the stated goals necessitates the creation of effective incentives and the attraction of external investments. The European Union demonstrates substantial efforts to support steelmakers in transitioning to environmentally friendly technologies. EU countries provide assistance in various forms, such as direct grants, preferential loans, and operational cost reimbursements. According to GMK Center, the total investment under these programs amounts to €14,6 billion [12]. Ukraine, aspiring to integrate into the EU, should actively participate in similar initiatives. This includes securing funding from European programs, establishing state support mechanisms, and developing incentives for industry «greening». Such measures will not only contribute to achieving climate goals but also enhance the competitiveness of Ukrainian metallurgy in the global market.

Conclusions.

The article examined the structure of steel production in Ukraine, highlighting a significant decline in output caused by extensive destruction resulting from Russia's full-scale aggression. Key steel production technologies were analyzed, and critical directions for modernization were outlined. The priority tasks identified include:

– Transitioning to DRI-EAF production using green hydrogen, which will facilitate the «greening» of the industry;

– Establishing electric steelmaking capacities for processing steel scrap;

– Implementing CCUS (carbon capture, utilization, and storage) technologies to improve the environmental performance of converter steel production.

Achieving these goals requires coordinated efforts by the government, industrial enterprises, and international stakeholders. Investments in «green» technologies will

not only align Ukraine with global sustainable development trends but also ensure the resilience and competitiveness of its metallurgical sector in the post-war period.

Special emphasis was placed on the necessity of securing funding from international organizations, external partners, and the state, as this will form the foundation for the successful transformation of the industry.

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