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COMPARING THE ENVIRONMENTAL PERFORMANCE OF STEELMAKING TECHNOLOGIES

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The study focuses on the pressing issue of environmental responsibility in the steel industry. Traditional steel production methods are associated with significant greenhouse gas emissions and have a negative impact on the environment. As environmental regulations are tightening and public interest in sustainable development is growing, the search for new, more environmentally friendly solutions is becoming increasingly important. Innovation in the steel industry is not just a trend, but a necessity for the industry's long-term survival. The proposed comprehensive approach to modernising steel production will help "ZAPORIZHSTAL" PJSC remain a major player in the steel market. Government support and investments in the development of green technologies are key to the successful transformation of the industry. The article analyses the potential of innovative technologies such as direct reduction of iron (DRI) and electric arc furnaces (EAF) to significantly reduce carbon dioxide emissions and improve energy efficiency. It also examines the role of carbon capture, use and storage technologies in minimising the negative impact on the climate. The results of the study show that the introduction of green technologies not only helps to reduce the environmental burden, but also opens up new opportunities for the export of Ukrainian steel to European markets, where environmental standards are increasingly important, and helps to facilitate rapid integration into the European Union and establish Ukraine as a sustainable player in the steel market. In addition, the transition to green metallurgy will help improve Ukraine's energy security by reducing dependence on energy imports. The introduction of innovative solutions helps to increase the competitiveness of steelmaking companies in the global market and ensure the long-term sustainability of the industry.

Key words: *Metallurgical industry, green metallurgy, environmental impact, CBAM, DRI, EAF, transformation.*

Тимошенко Даніїл, Кухар Володимир, Волкова Вікторія, Чуб Наталія, Кириченко Ігор. Порівняння екологічних показників сталеплавильних технологій

Дослідження присвячено актуальній проблемі екологічної відповідальності металургійної промисловості. Традиційні методи виробництва сталі супроводжуються значними викидами парникових газів і негативно впливають на навколишнє середовище. З огляду на посилення екологічних норм та зростання суспільного інтересу до сталого розвитку, пошук нових, більш екологічно безпечних рішень стає дедалі актуальнішим. Інновації в металургії – це не просто тренд, а необхідність для виживання галузі в довгостроковій перспективі. Запропонований комплексний підхід до модернізації металургійного виробництва допоможе «Запоріжсталі» залишатися великим гравцем на ринку металургії. Державна підтримка та інвестиції в розвиток «зелених» технологій є ключовими для успішної трансформації галузі. У статті проаналізовано можливості використання інноваційних технологій, як-от пряме відновлення заліза (DRI) та електродугові печі (ЕДП), для значного скорочення викидів вуглекислого газу та підвищення енергоефективності. Також розглядається роль технологій уловлювання, використання та зберігання вуглецю в мінімізації негативного впливу на клімат. Результати дослідження демонструють, що впровадження «зелених» технологій не тільки сприяє зменшенню екологічного навантаження, а й створює нові можливості для експорту української сталі на європейські ринки, де дедалі більшу роль відіграють екологічні стандарти, а також допомогає швидкій інтеграції до Євросоюзу та закріпленню як стійкого гравця на ринку металургії. Крім того, перехід на «зелену» металургію сприятиме підвищенню енергетичної безпеки України завдяки зменшенню залежності від імпорту енергоносіїв. Упровадження інноваційних рішень сприяє підвищенню конкурентоспроможності металургійних підприємств на світовому ринку та забезпеченню довгострокової стійкості галузі.

Ключові слова: *металургійна промисловість, зелена металургія, вплив на навколишнє середовище, CBAM, DRI, ЕДП, трансформація.*

Introduction. The metallurgical industry, a cornerstone of the global economy, finds itself at a crossroads of environmental challenges. Traditional geotechnological mining methods, which rely on transforming ore into a mobile state through thermal, mass-exchange, chemical, and hydrodynamic processes at the deposit site [1], coupled with production methods dependent on fossil fuels and energy-intensive processes, lead to significant CO_2 emissions and environmental damage. In the context of the global fight to reduce CO_2 emissions, it is clear that without radical changes, the metallurgical sector cannot ensure sustainable development.

Ukraine, with its powerful metallurgical complex, also faces a choice: continue exploiting outdated technologies or embark on a path of environmental modernization. The transition to green metallurgy is not just about implementing cutting-edge technologies, but also about a comprehensive transformation of the entire industry, including changing approaches to management and production organization.

Key areas of re-engineering metallurgical production include:

Technological Modernization:

1.1. Replacing blast furnaces with more environmentally friendly electric arc furnaces, which reduces CO_2 emissions [1; 2] and allows for the use of secondary raw materials (scrap metal).

1.2. Implementing direct reduced iron (DRI) technologies [2] using hydrogen as a reducing agent, which has the potential to fully decarbonize the steel production process [3].

1.3. Utilizing renewable energy sources to power production processes.

1.4. Implementing carbon capture and storage (CCS) systems to reduce greenhouse gas emissions.

Digitalization:

2.1. Applying artificial intelligence and machine learning to optimize production processes, predict and prevent emergencies.

2.2. Using the Internet of Things (IoT) to monitor and control equipment in real-time, improving efficiency and reducing maintenance costs.

2.3. Implementing digital twins to model and optimize production processes at the design stage.

Developing a Circular Economy:

3.1. Creating an efficient system for collecting, sorting, and processing scrap metal [4].

3.2. Developing technologies for processing metallurgical waste to obtain valuable materials.

3.3. Collaborating with other industries to create closed production and consumption cycles.

Collaboration and Innovation:

4.1. Establishing partnerships between metallurgical enterprises, research institutions, and government agencies to jointly solve problems and develop new solutions.

4.2. Supporting research and development in green metallurgy.

4.3. Creating a favorable investment climate to attract funding for modernization and innovation.

The urgency of this research is driven by the need to transform the Ukrainian metallurgical industry in response to global environmental challenges and growing pressure from international regulators (introduction of the CBAM carbon tax) [5]. Traditional steel production methods are characterized by high levels of greenhouse gas

emissions and negative environmental impacts. Implementing the principles of “green” metallurgy is critical for: reducing the industry’s environmental footprint and achieving sustainable development goals; and increasing the competitiveness of Ukrainian metallurgy in the global market [6].

The aim of the research is to justify the need for and develop ways to re-engineer metallurgical production in Ukraine for the transition to “green” steel and ensure the sustainable development of the industry.

Materials and methods. This article analyses pathways for re-engineering metallurgical production in Ukraine to transition towards “green” steel and ensure the industry’s sustainable development. This will be achieved through the implementation of innovative technologies, such as Midrex and electric arc furnaces (EAFs), to reduce CO_2 emissions and comply with CBAM requirements [7–9].

The research methodology employed a comprehensive approach combining in-depth analysis of actual data obtained from the automated emissions monitoring system at “ZAPORIZHSTAL” PJSC with a detailed comparative analysis of best industry practices, specifically Midrex technology for direct reduced iron production and electric arc furnace (EAF) steelmaking [10–12].

By combining these two approaches, the research provides a comprehensive understanding of the challenges and opportunities associated with the transition to green steel production in Ukraine. The analysis of real-world data from “ZAPORIZHSTAL” PJSC provides a baseline for understanding current emission levels and identifying areas for improvement. The comparative analysis of Midrex and EAF technologies highlights the potential for significant emissions reduction through the adoption of these innovative technologies. Furthermore, the continuous monitoring system at “ZAPORIZHSTAL” PJSC serves as a valuable case study for demonstrating the benefits of real-time emissions monitoring (fig. 1) The system’s ability to provide accurate and reliable data 24/7 has not only improved environmental safety but also enhanced production management by enabling proactive measures to minimize environmental impact.

This comprehensive approach provides a solid foundation for developing effective re-engineering strategies for the Ukrainian metallurgical industry. By leveraging both real-world data and best industry practices, the research aims to identify the most promising pathways for achieving sustainable development in the sector and complying with increasingly stringent environmental regulations.

Data analysis and visualization capabilities: The collected data can be analysed and presented in the form of graphs and reports, which allows for

Fig. 1. Automated emissions monitoring system at the sinter plant

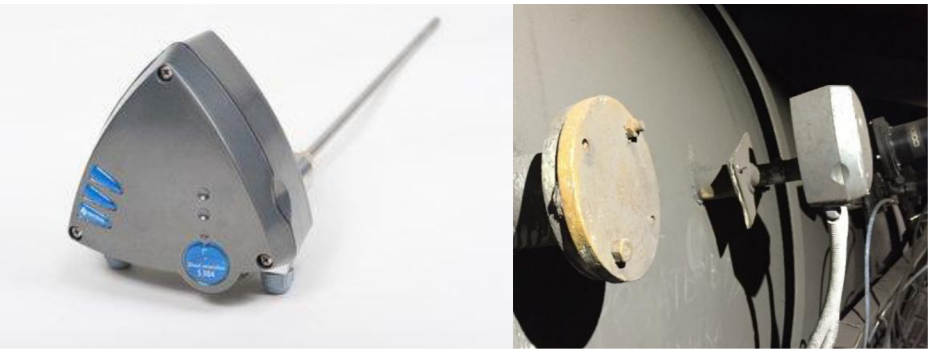

Fig. 2. Durag device used in aglodomain redistribution

Fig. 3. Sintrol S304 sensor used in blast furnace and OHF

the assessment of emission dynamics, identification of peak values, and determination of the effectiveness of environmental measures.

The company utilizes high-precision D-R 808 dust monitoring sensors from Durag (Fig. 2.) in the ironmaking and steelmaking process, ensuring high measurement accuracy and integration into the plant-wide control system. This enables the monitoring of key technological parameters such as temperature, pressure, and gas flow, allowing for the tracking of process dynamics and identification of potential deviations.

In addition to the automated monitoring system, Sintrol S304 sensors (Fig. 3.) are also used in the blast furnace and open-hearth furnace areas. These sensors are designed to measure dust concentration in industrial gases and are characterized by high accuracy, reliability, and resistance to aggressive environments. The use of Sintrol S304 sensors allows for the acquisition of additional data on dust emissions in these areas, complementing the information obtained from the main automated control system. These sensors help improve the accuracy of emission monitoring and ensure more effective environmental management in these production areas.

The study used data from the automated emissions monitoring system at “ZAPORIZHSTAL” PJSC. This includes measurements of dust and sulfur dioxide concentrations in the flue gases of the sintering plant and blast furnaces, as well as data on dust emissions in the blast furnace and open-hearth furnace areas from Sintrol S304 and Durag sensors. Reference data from Midrex and Danieli were also used. This allows comparing actual emissions at “ZAPORIZHSTAL” PJSC with those achievable using advanced technologies and assessing the potential for emission reduction. The study used a comprehensive approach to analyze the effectiveness of transitioning to green technologies. It includes – sstatistical analysis of emissions data to identify trends, seasonal fluctuations, and correlations with technological parameters. Detailed comparison of actual emissions from blast furnace production with those of Midrex + EAF technology [13]. Use of modern sensors, instruments, data collection and transmission systems, and specialized software for visualization, analysis, and archiving. Application of automated control systems for optimal operation of gas cleaning units and control of technological parameters. The results presented in Table 1 for Midrex and EAF technologies from Danieli demonstrate a significant advantage in reducing CO_2 [14] emissions and other pollutants compared to the traditional blast furnace-basic oxygen furnace route and open-hearth furnace presented in Table 2. This, in turn, allows compliance with stringent environmental standards and avoids financial losses associated with the CBAM carbon tax [15–16].

Table 1

Emissions during work at the Midrex and chipboard installation

Process	CO_2	CO	DUST
Midrex	400	10	5
EAF	100	1	1
Σ	500	11	6

Table 2

Emissions in blast-furnace production with a OHF

Process	CO_2	CO	Пил	SO_2	NO_x
Agglomeration & blast furnace					
Agglomeration					
sintering	300	15	30	40	10
Blast furnace					
Coke combustion	1650	30	20	20	5
Tapping of iron and slag	55	10			
Blast furnace gas	50	10			
OHF					
Fuel combustion	300	10	10	10	5
Oxidation of impurities	35	5	5		
Σ	2390 kg/t	80 kg/t	65 kg/t	70 kg/t	20 kg/t

Analysis indicates that the existing emissions monitoring system at "ZAPORIZHSTAL" PJSC allows for effective control and management of emissions within the current regulatory framework. However, considering the introduction of the CBAM carbon tax and stricter environmental regulations in the EU, traditional steel production methods are unlikely to ensure compliance with the new standards.

Result. What problems might arise? First off all: Modernize the monitoring system, optimize production processes, implement green technologies, digitize production, develop a circular economy. Implementing these measures will help "ZAPORIZHSTAL" PJSC not only adapt to new environmental requirements but also increase production efficiency, reduce costs, and strengthen its position in the global market.

This jeopardizes the competitiveness of Ukrainian metallurgy in the European market. Benchmarking with Midrex + EAF technology (Fig. 4.) will allow for a comprehensive assessment of the potential for emission reduction at "ZAPORIZHSTAL" PJSC and the development of a detailed strategy for phased modernization of production, taking into account economic and environmental aspects. The research findings will help justify investments in environmental measures by demonstrating their economic efficiency and positive impact on the environment, promoting greater corporate environmental responsibility.

Implementing a modern monitoring system and a modernization strategy based on the research results will enhance the company's environmental responsibility. This will positively impact its reputation, attract new investments, and ensure sustainable development in the long term. "ZAPORIZHSTAL" PJSC is committed to minimizing its environmental impact and is actively pursuing a range of initiatives to reduce emissions. This includes investing in cutting-edge technologies, optimizing existing processes, and transitioning towards a circular economy model to ensure sustainable steel production.

The Midrex + EAF technology demonstrates a significant reduction in CO_2 emissions (up to 70 %) compared to traditional blast furnace ironmaking. This is due to the elimination of coke production and the blast furnace, which are major sources of CO_2.

Ignoring CBAM requirements indeed carries significant financial risks for Ukrainian metallurgical enterprises. The carbon tax could amount to tens of millions of euros annually for large producers. This will substantially impact the profitability of steel exports to the EU.

Conclusions. The study showed that traditional steelmaking methods have a significant negative

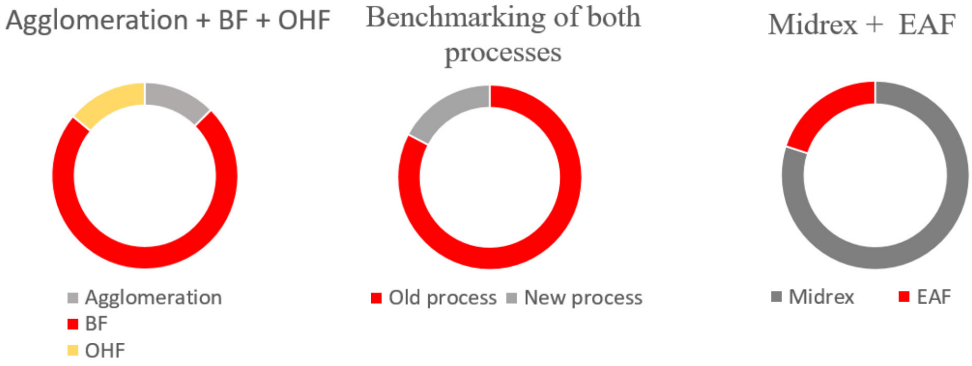

Fig. 4. Benchmarking of the legacy process with the newest process

impact on the environment, with 2390 kg/t of greenhouse gas emissions. A comparative analysis of different technologies showed that the transition to electric arc furnaces and direct reduction technologies can reduce emissions by 500 kg/t or more, which significantly reduces the carbon footprint of steel production. The introduction of modern emission monitoring systems has helped to effectively control and reduce pollution. The benchmark demonstrated that modernisation can reduce emissions by 70 %, and investments in environmentally friendly technologies pay off by reducing operating costs and increasing the company's competitiveness.

Overall, the study confirms that reengineering Ukraine's steel industry based on the principles of green metallurgy is not only a necessary step towards achieving environmental goals, but also a cost-effective solution.

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