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STRATEGIC MODERNIZATION OF PJSC «ZAPORIZHSTAL» FOR DECARBONIZATION AND ADAPTATION TO CBAM REQUIREMENTS

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In the context of the global fight against climate change and the tightening of regulatory restrictions, such as the introduction of the European Union's Carbon Border Adjustment Mechanism (CBAM), Ukrainian metallurgical enterprises face serious challenges that require urgent solutions. For PJSC «Zaporizhstal» these challenges manifest in the need not only to reduce CO_2 emissions but also to comply with new international environmental standards, which is critical for maintaining the competitiveness of their products in global markets. This article provides a comprehensive analysis of both economic and environmental risks associated with greenhouse gas emissions at PJSC «Zaporizhstal». The authors explore potential modernization pathways aimed at reducing the carbon footprint and improving environmental performance. Special attention is given to the implementation of advanced technologies such as Direct Reduced Iron (DRI) and Electric Arc Furnaces (EAF), which are promising solutions for the decarbonization of metallurgical production. The article presents the results of a detailed benchmarking of CO_2 emissions at PJSC «Zaporizhstal» compared to European producers. The dynamics of metal product production, particularly hot-rolled coil (HRC), are analyzed, and changes in the margin of this product after the implementation of modernization measures are assessed. The economic feasibility of investments in «green» metallurgy technologies, which provide not only environmental efficiency but also economic benefits for the enterprise, is emphasized. The research results demonstrate that strategic modernization of PJSC «Zaporizhstal» is a key factor for ensuring the long-term sustainable development of the enterprise. Modernization will contribute to job preservation, increased productivity, and competitiveness of the enterprise in the international market. Additionally, adaptation to the requirements of the «green» transition will enable Ukrainian metallurgy to successfully integrate into global supply chains that consider environmental responsibility as a key criterion for evaluating production efficiency.

Keywords: *CBAM, PJSC «Zaporizhstal», CO_2 emissions, modernization, direct reduction iron, electric arc furnaces, «green» steel, sustainable development, energy efficiency.*

Statement of the problem

Global warming and related climate changes are prompting the global community to take active measures towards the decarbonization of the economy. The European Union is taking a leading role in this process by implementing a set of tools to reduce the carbon footprint of products and the environmental burden on ecosystems. One such mechanism is the Carbon Border Adjustment Mechanism (CBAM), which introduces a carbon duty for importers of products with a high level of greenhouse gas emissions, including steel, aluminum, and cement. The introduction of this mechanism was preceded by extensive consultations, analytical studies, and preparatory work [1-3].

The current version of the CBAM provides for a transitional period starting from October 1, 2023, during which importers must report emissions associated with imported products, with the actual duty to be introduced from January 1, 2026. Initially, the CBAM will apply to a limited range of goods but may be expanded in the future. This creates new challenges for Ukrainian exporters, particularly for metallurgical enterprises whose products traditionally have a significant carbon footprint [4, 5].

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In this context, PJSC «Zaporizhstal», one of the largest Ukrainian metallurgical enterprises oriented towards European markets, must adapt to the new regulatory conditions to maintain its competitive advantages and ensure sustainable development. The introduction of the CBAM mechanism threatens the competitiveness of the plant, as its products may lose attractiveness to European consumers due to high CO_2 emissions. Therefore, adapting the enterprise to the CBAM requirements is an urgent task, the resolution of which depends on its further functioning and the preservation of jobs.

Thus, the study aims to justify the technological transformation of PJSC «Zaporizhstal» in response to CBAM requirements by analyzing emission-related risks, assessing modernization scenarios, and evaluating their impact on the enterprise's competitiveness and sustainability.

Analysis of the latest achievements on the identified problem

In analyzing current trends in the development of the metallurgical complex in well-known studies [6], the following key directions for its further evolution were identified: modernization of traditional blast furnace and converter production through innovative solutions; transition to electric arc furnaces (EAF); development of direct reduction of iron ore (DRI) technologies, including the use of hydrogen as a reducing agent; improvement of energy efficiency and decarbonization of production; implementation of circular economy principles, including increased recycling of steel scrap; and digitalization and implementation of Industry 4.0 approaches in metallurgical enterprises.

As noted in [7, 8], the metallurgical sector plays a significant role in the carbon footprint of the entire industrial complex, necessitating rapid transformation towards climate neutrality. Innovations in «green» metallurgy and hydrogen technologies are becoming particularly relevant. Projects involving the use of hydrogen to reduce iron ores (hydrogen-based DRI), implementation of carbon capture and storage technologies (CCS/CCUS), as well as advanced electric smelting units are being actively explored and tested in leading metallurgical countries.

Moreover, it is important to consider not only technical feasibility but also the economic and infrastructural conditions for the implementation of such transformations, particularly for enterprises operating in transition economies.

Purpose and task statement

The objective of this study is to provide a comprehensive justification for the technological transformation of a large metallurgical enterprise in the context of the transition to low-carbon production. This is achieved through the analysis of CO_2 emission levels, assessment of energy consumption in current and prospective production processes (particularly DRI and EAF technologies), comparison of their efficiency with European counterparts, development of a step-by-step decarbonization roadmap, and economic forecasting of modernization outcomes, taking into account the requirements of the Carbon Border Adjustment Mechanism (CBAM), investment feasibility, and the impact on product competitiveness in international markets.

Materials and methods

This study utilizes various sources of information, including:

- actual data on CO_2 emissions at PJSC «Zaporizhstal»;
- annual reports and public materials of the company;
- scientific publications and analytical reviews dedicated to the CBAM mechanism and issues of decarbonization in the metallurgical industry.

For data analysis and processing, the following methods were applied:

- system analysis – to identify the interrelationships between factors affecting CO_2 emissions;
- economic and statistical modeling – to assess the economic feasibility of various technical modernization options;
- expert evaluation method – to account for qualitative factors that are difficult to formalize.

Summary of the main material

The benchmarking of CO_2 emissions (fig. 1) revealed that the emission levels at PJSC «Zaporizhstal» exceed those of similar enterprises in EU countries. The main reason for this is the use of outdated technological processes, particularly the open-hearth steelmaking method, which has significantly higher carbon intensity compared to electric arc or converter (BOF) methods [9]. In the context of the CBAM mechanism, this creates additional threats to the export capacity of the enterprise and highlights the urgent need for production modernization.

The analysis showed that replacing open-hearth furnaces (OHF) with electric arc furnaces (EAF) combined with the implementation of direct reduced iron (DRI) technology significantly reduces CO_2 emissions. DRI technology involves the reduction of iron from iron oxides (usually in the form of iron ore) using natural gas or hydrogen, without melting the ore. Particularly effective from an environmental standpoint is the use of hydrogen as a reducing agent, which allows for the production of so-called «green» pig iron with a minimal carbon footprint [10]. EAF, unlike open-hearth furnaces, operate on electrical energy instead of fossil fuels, which also contributes to the reduction of overall greenhouse gas emissions.

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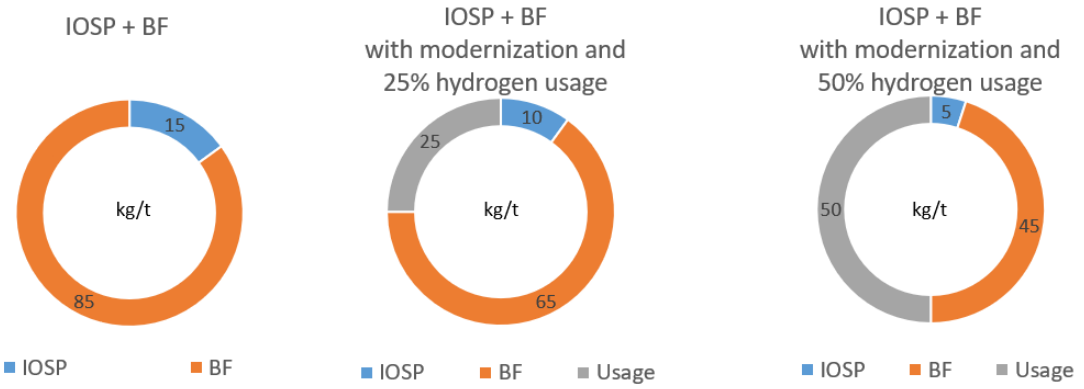

Fig. 1 – Dynamics of CO_2 emission reduction due to the modernization of the iron ore sintering plant (IOSP) and blast furnaces (BF)

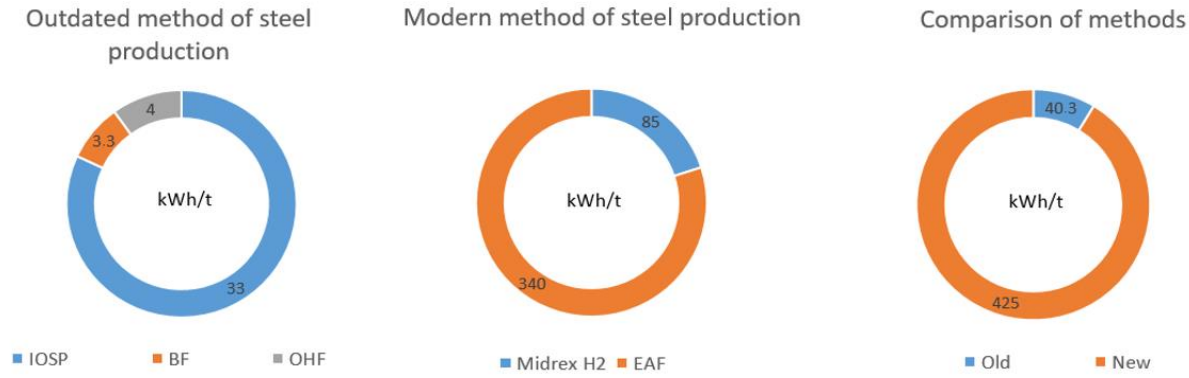

Fig. 2 – Comparative analysis of energy consumption for steel production using different technologies (Old = IOSP + BF + OHF; New = Midrex H_2 + EAF)

The benchmarking conducted (fig. 2) allowed for the comparison of the energy efficiency of key production technologies in metallurgy: the sintering section with an aspiration system, open-hearth furnace, Midrex H_2 DRI technology, and EAF. The results confirmed significant differences in energy consumption levels between traditional and low-carbon technologies [11, 12].

In previous studies, it was found that the specific energy consumption of the sintering plant is approximately 33 kWh/t, the blast furnace – 3.3 kWh/t, the open-hearth furnace – 4 kWh/t, Midrex H_2 – 85 kWh/t, and the electric arc furnace (EAF) – 340 kWh/t [9, 11]. A comparative analysis of different steel production methods revealed significant differences in their energy consumption levels. The traditional open-hearth process is less energy-efficient compared to modern EAF, but it is still used for the production of certain steel grades [11], particularly due to the technological inertia of enterprises.

The analysis showed that the Midrex H_2 technology, despite its high energy intensity, is a promising alternative to traditional steel production methods due to its significant reduction in CO_2 emissions. This is particularly relevant in the context of tightening environmental requirements. EAF, although characterized by relatively high energy consumption, have several advantages – including the flexibility of the production process and efficiency in recycling scrap metal. A comparative assessment of the energy efficiency of different technological approaches revealed significant differences between outdated methods (sintering and blast furnace production, open-hearth furnaces) and modern solutions such as Midrex H_2 and EAF. The implementation of the latter plays a key role in the decarbonization of the steel industry, contributing to the reduction of the carbon footprint and the overall energy efficiency of production [13, 14].

Therefore, the results of the analysis of steel production technologies used at PJSC «Zaporizhstal» indicate an urgent need to modernize production facilities to achieve environmental goals and maintain competitiveness in the international market. The transition from outdated open-hearth furnaces to modern electric arc furnaces, combined with the implementation of DRI technology, is considered a promising development direction that will significantly reduce CO_2 emissions and increase production energy efficiency. To maintain the competitiveness of the enterprise in the context of the «green» transition, production modernization is extremely necessary. This will allow compliance with international environmental standards, increase energy efficiency, and ensure the proper quality of products.

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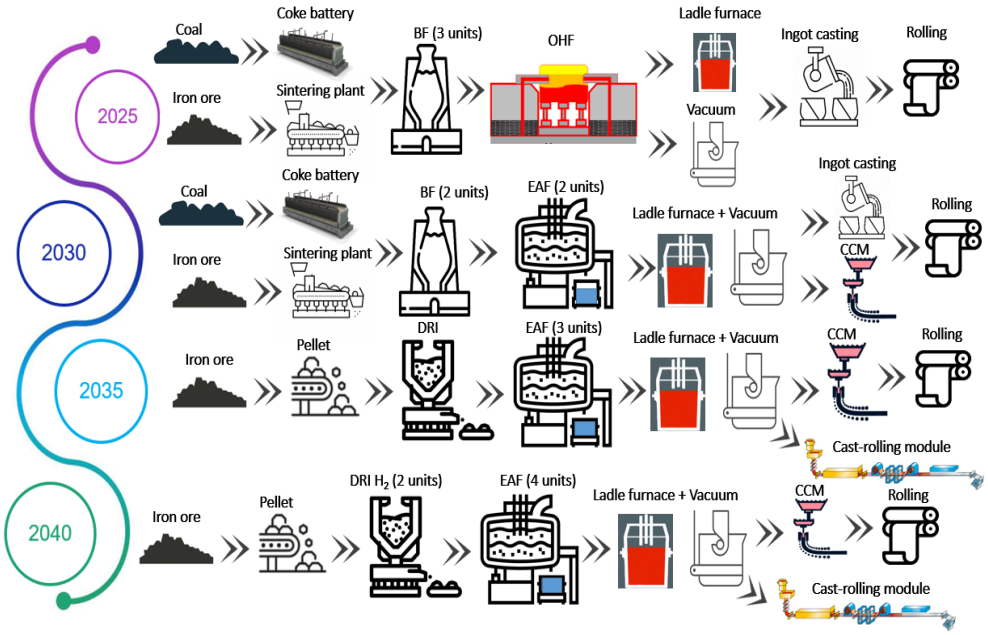

Fig. 3 – Roadmap for the phased decarbonization of metallurgical production

As a result of the analysis, a clear phased decarbonization plan was developed, presented in fig. 3.

This roadmap involves the gradual reduction of CO_2 emissions through the implementation of innovative technologies and energy-efficient solutions, similar to the breakthrough approaches realized under the ULCOS program in the EU [15, 16]. The phased approach allows for the rational distribution of capital expenditures (CAPEX) over time, reducing the financial burden on the enterprise.

Key stages of decarbonization include:

- Replacement of OHF with EAF – to significantly reduce CO_2 emissions and improve steel quality.
- Implementation of DRI technology using natural gas as an intermediate solution – this reduces dependence on fossil fuels and creates prerequisites for the subsequent transition to «green» hydrogen.
- Gradual transition to «green» hydrogen in DRI processes – as a long-term goal to minimize the carbon footprint.
- Implementation of energy-saving technologies and heat recovery systems to reduce energy consumption and increase economic efficiency.
- Integration of digital technologies – to optimize production processes and continuously monitor CO_2 emissions.The implementation of such a decarbonization roadmap will help Ukrainian metallurgical enterprises adapt to new environmental requirements, maintain their competitiveness, and ensure the sustainable development of the industry.

The implementation of technologies according to the decarbonization roadmap will not only reduce CO_2 emissions but also optimize production processes and expand the product range. In particular, PJSC «Zaporizhstal» can focus on the production of high-margin hot-rolled coil (HRC), which is characterized by stable demand in the global market and strategic importance for several industries.

The results of the production potential analysis confirmed the feasibility of installing a continuous casting machine (CCM) at PJSC «Zaporizhstal» as a strategic stage of modernization. The implementation of this project will allow the enterprise to respond flexibly to market demand, expand the product range by producing billets for further rolling at other Metinvest Group assets – particularly at European rolling facilities – and ensure diversification and increased production efficiency [16].

The forecasted dynamics of metal product production at PJSC «Zaporizhstal» after the implementation of the decarbonization roadmap (fig. 4) show expected stable growth in the output of hot-rolled coil (HRC), which, in turn, indicates the anticipated effectiveness of the chosen modernization strategy.

Taking into account the projected energy consumption and the requirements of the CBAM mechanism, a macro forecast for the development of PJSC «Zaporizhstal» has been formulated (fig. 5).

The calculation results demonstrate a stable average margin level for hot-rolled coil (HRC) at approximately USD 410 per ton, even considering the additional burden of the CBAM carbon tax. This indicates the relative resilience of the company's business model and the effectiveness of the proposed modernization strategy.

The implementation of the decarbonization roadmap allows PJSC «Zaporizhstal» not only to reduce its carbon footprint but also to ensure high production profitability in the long term. The forecasted dynamics of metal production indicate a positive impact of modernization on production volumes and overall efficiency.

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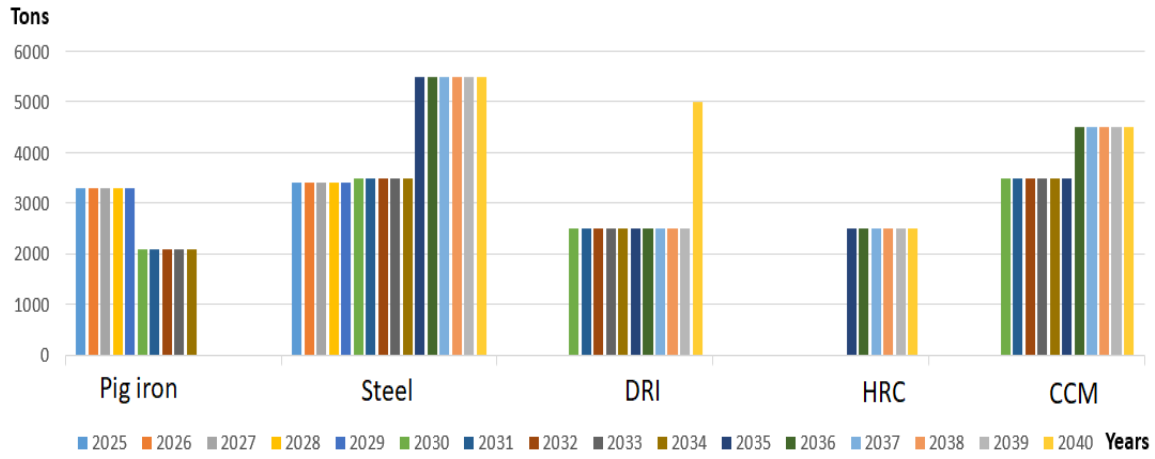

Fig. 4 – Forecasted dynamics of metal product production volumes at PJSC «Zaporizhstal» by year

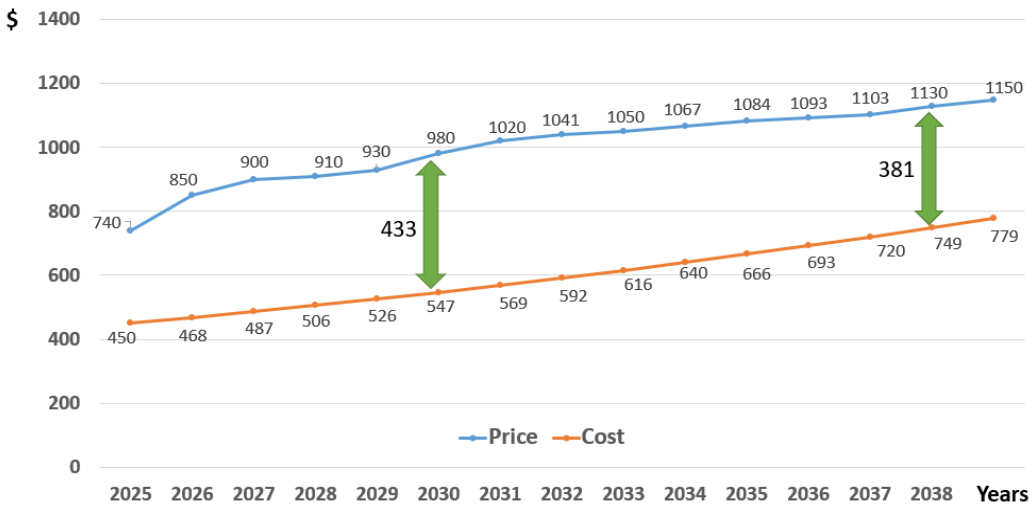

Fig. 5 – Macroeconomic forecast of profit margins in metal production

The economic efficiency calculation showed that production modernization is economically feasible despite significant capital expenditures. The reduction in energy costs and the carbon tax offsets the investments in modernization over the long term.

Conclusions

The conducted research confirmed that the modernization of PJSC «Zaporizhstal» is a critically important task for maintaining the company's competitiveness in the context of global decarbonization and the implementation of the CBAM carbon tax. The study established that the introduction of new technologies, including the transition to electric arc furnaces (EAF), the use of direct reduced iron (DRI) technology with hydrogen, and the integration of digital solutions, will significantly reduce CO_2 emissions to 613 kg per ton of steel. This meets modern EU environmental requirements and contributes to increased production energy efficiency.

Economic analysis showed that even with additional costs for the carbon tax, the average margin for hot-rolled coil (HRC) remains stable at USD 410 per ton, indicating the effectiveness of the company's business model post-modernization.

The proposed decarbonization roadmap involves phased emission reductions and a balanced distribution of capital investments, estimated at USD 10 billion, which reduces financial pressure on the company. The implementation of these measures will increase production capacity to 7 million tons of steel per year, ensure sustainable development, preserve jobs, and strengthen PJSC «Zaporizhstal's» position in the global market.

Thus, the modernization of PJSC «Zaporizhstal» is a strategic investment in the future of Ukrainian metallurgy, which will contribute to achieving the goals of the «green» transition and enable the company to make a significant

contribution to combating climate change. Successful project implementation requires state support in the form of preferential loans, tax incentives, and attracting investments for innovative projects, all of which will help integrate Ukrainian industry into the European economy.

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СТРАТЕГІЧНА МОДЕРНІЗАЦІЯ ПАТ «ЗАПОРІЖСТАЛЬ» ДЛЯ ДЕКАРБОНІЗАЦІЇ ТА АДАПТАЦІЇ ДО ВИМОГ СВАМ

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В контексті глобальної боротьби зі зміною клімату та посилення регуляторних обмежень, таких як впровадження Механізму коригування вуглецевих викидів на кордоні Європейського Союзу (СВАМ), українські металургійні підприємства стикаються із серйозними викликами, які потребують термінових рішень. Для ПАТ «Запоріжсталь» ці виклики проявляються у необхідності не лише скоротити викиди CO_2, а й відповідати новим міжнародним екологічним стандартам, що є критично важливим для збереження конкурентоспроможності їх продукції на світових ринках. У статті здійснено всебічний аналіз економічних та екологічних ризиків, пов'язаних із викидами парникових газів на ПАТ «Запоріжсталь». Автори досліджують можливі шляхи модернізації, спрямовані на зменшення вуглецевого сліду та покращення екологічних показників. Особливу увагу приділено впровадженню передових технологій, таких як пряме відновлення заліза і дугові сталеплавильні печі, які є перспективними рішеннями для декарбонізації металургійного виробництва. У статті наведено результати детального порівняльного аналізу викидів CO_2 на ПАТ «Запоріжсталь» у порівнянні з європейськими виробниками. Проаналізовано динаміку виробництва металургійної продукції, зокрема гарячекатаного прокату (в рулонах), а також оцінено зміни маржинальності цього продукту після реалізації заходів модернізації. Наголошується на економічній доцільності інвестицій у технології «зеленої» металургії, які забезпечують не лише екологічну ефективність, але й економічну вигоду для підприємства. Результати дослідження демонструють, що стратегічна модернізація ПАТ «Запоріжсталь» є ключовим фактором забезпечення довгострокового сталого розвитку підприємства. Модернізація сприятиме збереженню робочих місць, підвищенню продуктивності та конкурентоспроможності підприємства на міжнародному ринку. Крім того, адаптація до вимог «зеленої» трансформації дозволить українській металургії успішно інтегруватися у глобальні ланцюги постачання, які розглядають екологічну відповідальність як ключовий критерій оцінки ефективності виробництва.

Ключові слова: *СВАМ, ПАТ «Запоріжсталь», викиди CO_2, модернізація, пряме відновлення заліза, дугові сталеплавильні печі, «зелена» сталь, сталий розвиток, енергоефективність.*

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