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Review article
Обзорная статья

ADAPTATION TO CLIMATE CHANGE IN AN INDUSTRIAL REGION WITH STEEL PRODUCTION: REVIEW OF GLOBAL EXPERIENCE

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Abstract. Ferrous metallurgy is considered as one of the most difficult industries to decarbonize due to the high heat requirements of using carbon as a process feedstock, low profitability, high capital intensity, and long asset life. The authors review the latest researches in the field of technology and practice of decarbonization of cast iron and steel production. The paper evaluates existing and new decarbonization methods, as well as potentially revolutionary technologies. The analysis showed that there are several promising ways to produce iron on an industrial scale without CO_2 emissions. Currently, two advanced technologies for carbon-free steel production are at the stage of piloting and transition to demonstration projects. These are direct reduction of iron with "green" electrolytically produced hydrogen and direct electrolysis of iron ore. The review focuses on innovative technologies for carbon capture, use and storage (CCUS), especially promising technologies such as carbonization of steelmaking slags. The authors discuss the existing barriers to decarbonization and the tools that can help to overcome them. In general, although advanced decarbonization technologies are key levers for reducing emissions, they are still very expensive and are mostly at the pilot stage. From an economic point of view, it is more profitable to modernize existing facilities using CCUS than to build new facilities using alternative technologies. The review also highlights gaps in previous research works.

Keywords: climate change, climatically active gases, decarbonization of steel production, scrap use, technologies for carbon capture, use and storage, steelmaking slags carbonization, direct reduction iron, iron ore electrolysis

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АДАПТАЦИЯ К ИЗМЕНЕНИЯМ КЛИМАТА В ПРОМЫШЛЕННОМ РЕГИОНЕ ПРИ ПРОИЗВОДСТВЕ СТАЛИ: ОБЗОР МИРОВОГО ОПЫТА

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Аннотация. Черная металлургия считается одной из самых сложных отраслей для декарбонизации из-за высоких требований к теплу использования углерода в качестве технологического сырья, низкой рентабельности, высокой капиталоемкости и длительного срока службы активов. Авторы рассматривают новейшие исследования в области технологии и практики декарбонизации производства чугуна и стали. В обзоре оцениваются существующие и новые методы декарбонизации, а также потенциально революционные технологии. Проведенный анализ показал, что существует несколько перспективных способов производства железа в промышленных масштабах без выбросов CO_2. В настоящее время на стадии пилотирования и перехода к демонстрационным проектам находятся две передовые технологии безуглеродного получения стали. Это прямое восстановление железа «зеленым» электролитически полученным водородом и прямой электролиз железной руды. Особое внимание в обзоре уделено инновационным технологиям улавливания, использования и хранения углерода (CCUS), в особенности такой перспективной технологи, как карбонизация сталеплавильных шлаков. Рассматриваемые в обзоре существующие барьеры на пути к декарбонизации и инструменты могут помочь их преодолеть. В целом, хотя передовые технологии декарбонизации являются ключевыми рычагами для сокращения выбросов, пока они очень дороги и находятся в большинстве своем на стадии пилотирования. С точки зрения экономики, более выгодно модернизировать существующие объекты с помощью CCUS, чем строить новые мощности с использованием альтернативных технологий. Также в обзоре указаны пробелы в исследованиях.

Ключевые слова: изменение климата, парниковые газы, декарбонизация производства стали, использование лома, технологии улавливания и хранения углерода, карбонизация сталеплавильных шлаков, железо прямого восстановления, электролиз железной руды

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Introduction

The global iron and steel industry contributes approximately 7 % to total global greenhouse gas emissions, making it the highest among of all heavy industry sectors [1]. Ferrous metallurgy is an energy-intensive industry [2; 3], with energy costs accounting for a significant portion of steel production costs – from 20 to 40 % [4]. Therefore, many strategies for decarbonization of steel production involve energy conservation. Thus, the iron and steel industry significantly contributes to global greenhouse gas (GHG) emissions and, consequently, climate change.

In the Russian Federation, there is an urgent need for scientific research to reduce the carbon footprint of the iron and steel industry, taking into account regional differences. This issue is of particular importance, given that Western expert studies [5] have unjustifiably reported a high environmental impact for Russian industry and high per capita carbon emissions (three times higher than the global average), and these emissions are on the rise[1]. Greening production increases the resilience of enterprises, which is crucial in the context of unprecedented sanctions affecting the development patterns of the iron and steel industry.

This paper examines existing technologies and practices for decarbonization of iron and steel production and their implementation status as of early 2025. It also analyzes the potential for scaling up these technologies and the challenges that need to be overcome.

Existing technological innovations and examples of their implementation

In May 2021, the International Energy Agency (IEA) released a report [6], which was updated in 2023 [7]. This report proposed a path for the global energy sector to help achieve the goal of the Paris Agreement which is to limit the global temperature increase to 1.5 °C above pre-industrial levels and keep it below 2 °C. Although this document provided important guidance for policymakers, industry, and the financial sector, the target of the Paris Agreement was not met in 2024 according to the EU's Copernicus Climate Change Service (C3S)[2]. The International Energy Agency proposes so-called *near zero emission projects* – projects that have close to zero emissions from the outset after commissioning (Fig. 1).

According to IEA recommendations, it is planned that by 2050, the share of iron and steel production will account for 95 % of the total volume, as a result of implementing such projects (Table).

The simplest solution to reducing emissions is the use of scrap metal (EAF) and the introduction of clean electricity to replace fossil fuels. However, this method is limited by the availability of high-quality scrap. Innovative technologies such as *carbon capture, use, and storage* (CCUS), *electrolytic hydrogen-based direct reduction iron* (EHB DRI), and *iron ore electrolysis* (IOE) are the keys to reducing emissions, but they remain very expensive and are mostly at the pilot stage.

Carbon Capture, Use, and Storage (CCUS) technologies

CCUS technologies are implemented very slowly worldwide due to their high cost. When implemented in iron and steel production, they are among the most expensive compared to other industries[3] [8; 9]. However, the IEA insists that the lack of such technologies cannot help achieving zero emissions targets. In the iron and steel industry, CCUS technologies have proven to be the least expensive low-carbon options compared to other technologies. It is believed that upgrading existing facilities using CCUS (*Carbon Capture, Utilization, and Storage*) is more cost-effective than building new facilities using alternative technologies. The main challenge is that steelmaking does not produce pure carbon dioxide.

[1] UNEP – Emissions Gap Report 2024. URL: https://wedocs.unep.org/20.500.11822/46404 (Accessed: 08.07.2025).

[2] Copernicus Climate Change Service – Global Climate Highlights Report 2024. URL: https://globalclimaterisks.org/temperature/global-climate-highlights-2024-copernicus-report-2024-officially-the-hottest-year-on-record/ (Accessed: 08.07.2025).

Plans for the use of decarbonization technologies in cast iron and steel production [7]

Планы по долям использования технологий декарбонизации производства чугуна и стали [7]

Process	Year			
	2022	2030	2035	2050
Share of scrap metal in steel production feedstock, %	33	38	40	48
Share of near-zero-emission cast iron production, %	0	8	27	**95**
Share of CCUS technology in steel production, %	0	3	10	37
Share of electrolytic hydrogen for direct steel reduction, %	0	5	15	44
Share of steel produced by ore electrolysis, %	0	0	2	14

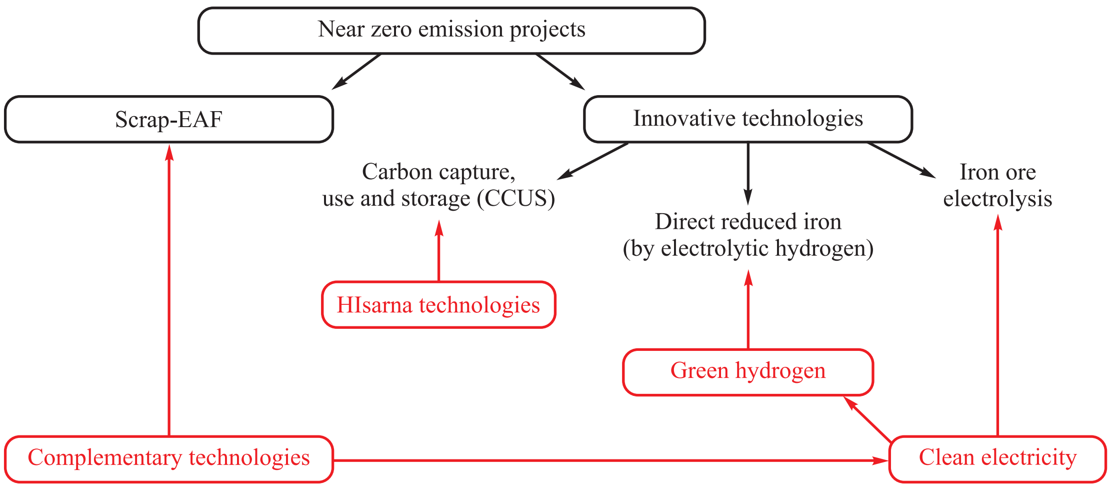

Fig. 1. Near zero emission projects and their complementary technologies

Рис. 1. Проекты с почти нулевым уровнем выбросов и сопутствующие технологии

When iron is smelted in a blast furnace using coal coke, the resulting blast furnace gas contains 12 – 20 % CO_2, 20 – 30 % CO, up to 0.5 % CH_4, 1 – 4 % H_2, and 55 – 58 % N_2 [10]. Flue gases also contain carbon monoxide and nitrogen oxides. The first CCUS projects in the iron and steel industry have already been launched. Since 2016, a commercial CO_2 capture project has been operating in Abu Dhabi (UAE) at a steel plant with a capacity of 0.8 million tones CO_2 per year. The gas is sent to oil production facilities to improve the efficiency of oil recovery. In 2022, PJSC Severstal was mentioned as actively developing CCUS in the iron and steel industry[4]. The innovative HIsarna iron production technology, developed under the *Ultra-Low CO_2 Steel* (ULCOS) program [11] by Tata Steel Europe, allows simplifying the capture of carbon dioxide. Recent pilot tests of HIsarna have successfully demonstrated a reduction in CO_2 emissions [12]. Other benefits of the HIsarna process include the ability to use low-grade iron ore and a variety of fuels (from thermal coal and gas fuels to biomass) instead of coking coal, as well as the ease of capturing most CO_2. The HIsarna process involves partial pre-reducing iron ore pellets in the upper section of the BOF (CCF) and iron smelting in the lower section of the smelting reduction vessel (SRV) using the HIsmelt technology. Developers believe that the HIsarna technology has good potential as an alternative to blast furnace production.

One variation of CCUS technology is CO_2 capture in mineral systems, which results in the formation of carbonate compounds. Industrial waste, including slags, is alternative mineral feedstock. Carbonation can be achieved using both direct and indirect methods (Fig. 2).

According to the recent estimates [13; 14], nearly a half of the direct reduction in CO_2 emissions can be attributed to the mineralization of steel slag. Steel slag was originally considered as waste and disposed of in landfills. However, efforts are underway to redirect some types of slag from landfills to use as environmentally friendly binders and quarry aggregates [15 – 21].

[3] UNECE – Technology brief carbon capture, use and storage (CCUS). URL: https://www.readkong.com/page/technology-brief-carbon-capture-use-and-storage-ccus-3054486 (Accessed: 10.07.2025).

[4] Technology brief carbon capture, use and storage (CCUS) 2022. URL: https://www.skoltech.ru/app/data/uploads/2022/11/CCUS-Skolteh-2022–11–10.pdf (Accessed: 13.07.2025).

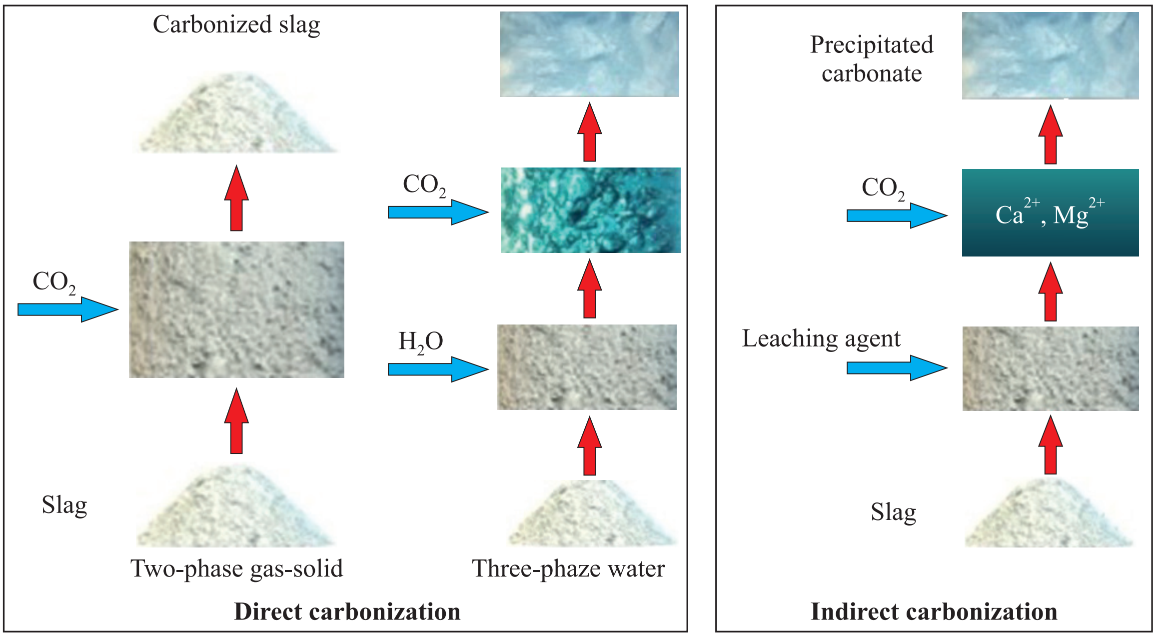

Fig. 2. Methods of slags carbonization

Рис. 2. Методы карбонизации шлаков

The research has shown that carbonization of steel slag improves its properties making it more durable and chemically active [22; 23]. These developments are promising for future applications such as the production of road surfaces, cement, and concrete products [24 – 26].

However, the potential of CO_2 mineralization has been questioned due to the high energy costs needed to overcome slow reaction kinetics. Although studies in this area are still in their early stages, they already have significant scientific and practical implications, especially due to the current need to achieve carbon neutrality.

Technologies based on the electrolytic production of hydrogen and its use in direct reduction

The first steel produced using direct reduction hydrogen technologies was developed in 2021 by the Swedish company SSAB under the Swedish HYBRIT[5] (*Hydrogen Breakthrough Ironmaking Technology*) project. As the direct reduction technology based on "green" hydrogen holds great promise and has the potential to revolutionize the iron and steel industry, it requires significant R&D investment to bring it to scale. Only the first HYBRIT pilot projects are underway followed by large-scale demonstration projects with a capacity of 1.3 Mt and then full commercialization by 2030 – 2040. Notably, "green" electrification of the industry requires access to significant amounts of electricity from renewable sources. Thus, fossil-free steel production in the HYBRIT project will annually require approximately 10 – 15 TWh of electricity [27]. A similar technology is being developed by ArcelorMittal in Germany. Under the HyBit (*Hydrogen for Bremen's industrial transform*) project, the installation of hydrogen electrolyzers began at the Bremen steelworks in October 2024. The Bremen steelworks annually emits approximately 4.6 million tones CO_2, making it the seventh-largest polluting industrial plant in Germany [28]. The transition to hydrogen technologies aims to improve this situation.

In Russia, recent studies have also explored the feasibility of hydrogen production using electrolysis. This involves generating electricity from wind power plants and then using it in the industrial process of direct iron ore reduction to produce "green" steel [29]. The prospects for developing hydrogen technologies in the domestic iron and steel industry are being explored [30; 31].

Notably, the transition to the use of "green" hydrogen occurs under significant uncertainty. Hydrogen has not yet been widely adopted or integrated into specific energy policies, and there are no clear details or conditions regarding the distribution of public funds to facilitate the transition to hydrogen. It is important to understand that by 2050, in Europe alone, the production of decarbonized steel based on hydrogen obtained through electrolysis will increase the electricity demand for the iron and steel industry by approximately 11 % (or 183 TWh). In the context of decarbonization, this demand should be met by increasing the production of "clean energy" from wind and solar sources [29].

[5] SSAB – Fossil free steel. URL: https://www.ssab.com/en/fossil-free-steel (Accessed: 08.07.2025).

Iron ore electrolysis technologies

The transition to a low-carbon economy requires changes in iron and steel production methods. Two electrolysis approaches are currently being explored. The first one is the ULCOWIN electrolysis process (ULCOS project) when iron ore grains are suspended in an alkaline sodium hydroxide solution at 110 °C resulting in a solid iron product [33]. A pilot plant with a capacity of 5 kg of iron per day has been proposed [34]. Second, iron production through molten iron oxide electrolysis [35] is a new technology developed by the Massachusetts Institute of Technology (MIT), for which laboratory research has been completed. This process produces iron that is completely carbon-free. The gas component produces only oxygen, not carbon dioxide. Molten oxide electrolysis, in which iron ore is dissolved in a mixed oxide solvent (such as silica or calcium oxide), occurs at a temperature of approximately 1600 °C. The resulting molten iron is collected at the bottom of the cell and pumped out. Since electrolysis produces no CO_2, the process could theoretically be considered carbon-neutral, but only if the electricity required to power the process is generated with zero CO_2 emissions. There are several engineering challenges that need to be addressed before electrolysis becomes economically viable.

Conclusions

Overall, various projects are underway globally to develop and implement the low-CO_2 steelmaking technologies. Potential significant reductions in greenhouse gas emissions in the iron and steel industry are constrained by current technologies, the quality of iron ore raw materials, and the availability of low-carbon fuels, hydrogen, and zero-carbon energy. The decarbonization of the iron and steel industry will be impossible without new innovation-intensive technologies, without maximizing the potential of secondary energy resources at ironworks, and without introducing renewable energy sources. The CCUS industry in Russia is still in its early stages, but the current climate agenda clearly encourages the Russian companies to consider this decarbonization method.

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