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EKOLOGIK TOZA METALLURGIYA: BARQAROR AMALIYOTLAR, YASHIL TEXNOLOGIYALAR VA MATERIAL INNOVATSIYALARI

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Annotatsiya. Mazkur maqolada barqaror metallurgiya amaliyotlarining keng qamrovli sharhi, jumladan past-uglerodli eritish, qayta ishlash, vodorodga asoslangan tiklash hamda energiya samaradorligi yuqori bo‘lgan qotishmalarni ishlab chiqarish tahlil qilingan. Kukunli metallurgiya, additiv ishlab chiqarish va eritmasiz ekstraktsiya kabi ilg‘or yashil texnologiyalar baholangan. Atrof-muhit barqarorligini ta'minlash maqsadida hayot tsikli baholash (LCA), kompyuterli modellashtirish va jarayonlarni optimallashtirish integratsiyasi muhokama qilingan. Tadqiqotda yangi ekologik toza qotishmalar, sanoat miqyosida joriy etish hamda yashil metallurgiyani rag‘batlantiruvchi me'yoriy bazalar yoritilgan. Tahlil natijalari shuni ko‘rsatdiki, vodorodli tiklash usuli CO_2 chiqindisini 70–90 % ga kamaytirish, metallolomdan qayta foydalanish esa energiya iste'molini 50–60 % ga kamaytirish imkonini beradi.

Kalit so‘zlar: ekologik toza metallurgiya; barqaror jarayonlar; yashil texnologiyalar; qayta ishlash; past-uglerodli eritish; vodorodli tiklash; hayot tsikli baholash; barqaror qotishmalar; aylanma iqtisodiyot; kukunli metallurgiya.

Аннотация. В настоящей статье представлен комплексный обзор устойчивых металлургических практик, включая низкоуглеродную плавку, переработку, водородное восстановление и энергоэффективное производство сплавов. Оценены передовые зелёные технологии, такие как порошковая металлургия, аддитивное производство и экстракция без растворителей. Обсуждается интеграция оценки жизненного цикла (LCA), компьютерного моделирования и оптимизации процессов с точки зрения экологической устойчивости. В исследовании также рассматриваются новые экологически чистые сплавы, внедрение на промышленном уровне и нормативно-правовые рамки, способствующие развитию зелёной металлургии. Результаты анализа показали, что метод водородного восстановления позволяет снизить выбросы CO_2 на 70–90 %, а переработка металлолома — снизить энергопотребление на 50–60 %.

Ключевые слова: экологически чистая металлургия; устойчивые процессы; зелёные технологии; переработка; низкоуглеродная плавка; водородное восстановление; оценка жизненного цикла; устойчивые сплавы; циркулярная экономика; порошковая металлургия.

Abstract. This paper provides a comprehensive review of sustainable metallurgical practices, including low-carbon smelting, recycling, hydrogen-

based reduction, and energy-efficient alloy production. Advanced green technologies such as powder metallurgy, additive manufacturing, and solvent-free extraction are evaluated. The integration of life-cycle assessment (LCA), computational modeling, and process optimization for environmental sustainability is discussed. The study also highlights emerging eco-friendly alloys, industrial-scale implementation, and regulatory frameworks promoting green metallurgy. The analytical results showed that the hydrogen reduction method enables a reduction of CO_2 emissions by 70–90 %, and scrap recycling enables a reduction of energy consumption by 50–60 %.

Keywords: eco-friendly metallurgy; sustainable processes; green technologies; recycling; low-carbon smelting; hydrogen reduction; life-cycle assessment; sustainable alloys; circular economy; powder metallurgy.

1. INTRODUCTION.

Metallurgy is a cornerstone of modern industry, underpinning sectors ranging from construction and transportation to electronics and energy. However, conventional metallurgical processes consume enormous amounts of energy and contribute to environmental degradation. Steel production alone accounts for approximately 7–9 % of global CO_2 emissions, while smelting and refining processes release sulfur dioxide, nitrogen oxides, and heavy metal pollutants. Additionally, slag, tailings, and wastewater generate ecological hazards, affecting soil, water, and air quality [1, 2].

Eco-friendly metallurgy focuses on minimizing environmental impact while ensuring material quality, reliability, and cost-effectiveness. Achieving this goal requires integrating green technologies, process optimization, waste minimization, and energy efficiency. The principles of sustainable metallurgy include reducing carbon emissions, recovering secondary resources, lowering energy consumption, and designing materials for recyclability [3].

Recent advancements in computational thermodynamics, process simulation, and additive manufacturing provide tools for eco-efficient material design. For example, hydrogen-based steelmaking reduces CO_2 emissions by replacing carbon with hydrogen as a reducing agent. Recycling and remelting of scrap metals conserve natural resources and reduce energy demand. Powder metallurgy and near-net-shape fabrication minimize material waste, enabling more sustainable production cycles [4].

With the adoption of Decree No. PF-78 of the President of the Republic of Uzbekistan dated 14 October 2022 "On accelerating the transition to a green economy until 2030", comprehensive efforts to introduce green technologies into industry have begun in Uzbekistan. This strategic document creates new opportunities and obligations for the metallurgical sector. The aim of this study is

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to review contemporary eco-friendly metallurgical practices, highlighting technological innovations, microstructural control, environmental benefits, and future prospects. By examining both industrial-scale implementation and emerging research, the study provides a roadmap for transitioning conventional metallurgy to a greener, more sustainable paradigm.

2. RESEARCH METHODOLOGY.

This study was conducted as a systematic analytical review and included four principal methodological approaches. First, 65 peer-reviewed publications indexed in Scopus, Web of Science, and ScienceDirect databases for the period 2018–2024 were analyzed. The keyword search was performed using the terms "green metallurgy", "hydrogen reduction steelmaking", "sustainable alloy", "powder metallurgy", and "life-cycle assessment". Publications from journals with an impact factor not less than 2.0 and containing quantitative experimental data were included in the selection.

Second, the reports of the International Energy Agency (IEA) "Iron and Steel Technology Roadmap" (2020), the European Commission's "Critical Raw Materials Resilience" (2020), and the World Steel Association data were comparatively analyzed. These sources provided important information on industrial-scale implementation and environmental performance indicators.

Third, a comparative technology evaluation method was applied. For each green technology, the analysis was performed according to the following parameters: energy consumption (GJ/t), CO_2 emissions (t CO_2/t), required capital investment, and Technology Readiness Level (TRL) for industrial deployment.

Fourth, the life-cycle assessment (LCA) method was applied in accordance with ISO 14040:2006 and ISO 14044:2006 standards. The LCA approach enabled quantitative evaluation of the differences in environmental impact between conventional metallurgical processes and green alternatives. The data were statistically processed in Microsoft Excel 2021, and the main indicators were presented in percent, t CO_2/t, and GJ/t units.

3. RESULTS AND ANALYSIS.

3.1. Environmental challenges in conventional metallurgy

Traditional metallurgy faces several ecological challenges. First, a high carbon footprint — blast furnaces and smelting operations emit significant amounts of CO_2. Second, energy intensity — high-temperature processes require enormous electricity and fuel consumption. Third, air and water pollution — sulfur oxides, nitrogen oxides, particulate matter, and heavy metals affect local ecosystems. Fourth, solid waste generation — slag, tailings, and dust create long-term environmental liabilities. Fifth, resource depletion — mining consumes large quantities of iron ore, bauxite, and other metals, often impacting biodiversity [5].

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The environmental impacts of major metallurgical processes are summarized in Table 1.

Table 1.

Environmental impacts of conventional metallurgical processes

No.	Process	Energy use (GJ/t)	CO_2 emissions (t CO_2/t)	Major pollutants
1	Blast furnace (steel)	20–25	1.8–2.0	SO_2, NO_x, dust
2	Aluminum smelting	15–20	1.1–1.2	Fluorides, CO_2
3	Copper refining	10–12	0.6–0.8	SO_2, heavy metals

As can be seen from the table, steel production has the highest energy consumption and CO_2 emissions, which makes the introduction of green technologies in this sector the most priority direction from the standpoint of ecological efficiency.



Figure 1. Visual scheme of environmental metallurgy.

3.2. Green metallurgical technologies

Eco-friendly metallurgy employs multiple strategies to reduce environmental impact. Each direction is examined in detail below.

Low-carbon and hydrogen-based reduction. Hydrogen-based direct reduction replaces carbon monoxide in ironmaking with hydrogen, producing water vapor instead of CO_2 [6]:

$$Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O$$

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This approach significantly reduces greenhouse gas emissions and provides a pathway to carbon-neutral steel production. In 2021, Sweden's SSAB company, within the HYBRIT project, started the world's first commercial steel production based on hydrogen reduction technology.

Recycling and circular metallurgy. Scrap recycling and secondary metal recovery minimize resource consumption and energy demand. Electric arc furnaces (EAF) efficiently remelt steel scrap, reducing energy use by approximately 50 % compared to traditional blast furnaces. Aluminum recycling saves up to 95 % of the energy needed for primary production.

Powder metallurgy and near-net-shape fabrication. Powder metallurgy (PM) allows precise alloy composition control and near-net-shape fabrication, minimizing machining waste. PM techniques, combined with additive manufacturing (3D printing), further enhance material utilization and energy efficiency while enabling the production of advanced alloys with complex geometries [7].

Eco-friendly alloying and coatings. Alloy design can improve corrosion resistance, reduce maintenance, and extend service life. Coatings that reduce oxidation and wear decrease energy and resource consumption by lowering component replacement frequency.

3.3. Comparative analysis of energy and emission saving strategies

The effectiveness of green metallurgy strategies is presented in Table 2.

Table 2.

Energy and emission savings through eco-friendly metallurgy

No.	Strategy	Energy saving (%)	CO_2 reduction (%)
1	Scrap recycling	50–60	40–50
2	Hydrogen reduction	30–50	70–90
3	Powder metallurgy	20–30	10–20
4	Near-net-shape fabrication	15–25	5–15

The analysis results show that hydrogen reduction is the most effective strategy for CO_2 emission reduction (70–90 %), while scrap recycling ranks first in energy saving (50–60 %). A combined approach — applying two or three strategies simultaneously — leads to the most effective results [8].

3.4. Microstructural control for sustainability

Microstructural engineering enhances both performance and environmental efficiency simultaneously. Grain refinement increases strength, allowing thinner,

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lighter components, thus reducing material usage. Phase stabilization reduces energy-intensive reprocessing and extends component service life. Nano-scale reinforcements improve mechanical performance and thermal resistance, decreasing frequent replacements. Residual stress management optimizes service life and minimizes failures, reducing environmental impact.

Advanced characterization techniques such as electron microscopy, X-ray diffraction, and computational modeling guide microstructural design to align with sustainability goals [9].

4. DISCUSSION.

The analysis conducted shows that the industrial-scale introduction of green metallurgy has several important advantages but is also associated with serious technical and economic challenges. First and foremost, the high capital cost is a significant constraint. New furnaces, hydrogen supply infrastructure, and additive manufacturing equipment require substantial investments. According to estimates, converting a conventional blast furnace into a hydrogen reduction plant requires 200–400 million euros of investment per 1 million t/year capacity [10].

The second important issue is feedstock quality. Consistent scrap or metal powder quality is critical for process stability. In the European Union, this issue is regulated through the Extended Producer Responsibility (EPR) system. Under Uzbek conditions, establishing a similar scrap collection and sorting system is an urgent task.

Process control complexity — multi-step processes require advanced monitoring and automation systems. The integration of artificial intelligence and digital twins opens up significant opportunities in this direction. According to McKinsey & Co analysis, AI-based optimization enables an additional 8–12 % reduction in energy consumption and compensation for feedstock quality variations.

Regulatory compliance — environmental regulations impose strict limits on emissions and waste handling, requiring robust compliance strategies. Early adoption in Europe and Asia shows that eco-friendly metallurgical practices reduce lifecycle costs and ensure positive public reception [11].

Under Uzbek conditions, the following directions are priorities for the development of green metallurgy: (1) development of electric arc furnace technology, especially at the Almalyk Mining and Metallurgical Combine and the Bekobod Metallurgical Plant; (2) improvement of the local scrap collection system; (3) launching hydrogen production projects associated with renewable energy sources; (4) development of strategic programs for retraining specialists and personnel.

5. FUTURE PERSPECTIVES

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Future research directions in the field of green metallurgy include:

–Industrial-scale hydrogen-based metallurgy;

–Integration of artificial intelligence and digital twins for real-time process optimization;

–Development of fully recyclable and lightweight alloys for sustainable infrastructure;

–Hybrid manufacturing combining additive and traditional methods for minimum waste;

–Policy frameworks incentivizing low-carbon and eco-friendly metallurgical practices globally [12].

For the metallurgical industry of Uzbekistan, the phased introduction of these directions will enable a 30–40 % reduction in CO_2 emissions and a 25–35 % increase in energy efficiency across the sector by 2030.

6. CONCLUSION.

Eco-friendly metallurgy represents a transformative approach to minimizing the environmental impact of metal production. Strategies such as hydrogen-based reduction, recycling, powder metallurgy, and microstructural optimization enable sustainable, energy-efficient, and high-performance material production. The main conclusions are formulated as follows:

First, the hydrogen-based reduction method is the most effective strategy for reducing CO_2 emissions by 70–90 % and opens the way to carbon-neutral steel production. Second, scrap recycling, by reducing energy consumption by 50–60 % and CO_2 emissions by 40–50 %, remains the most economically effective green technology. Third, powder metallurgy and additive manufacturing enable minimization of material waste and production of components with complex geometries.

Life-cycle assessment, process optimization, and regulatory compliance are critical to achieving these goals. By integrating innovative technologies with environmental stewardship, the metallurgical industry can significantly reduce energy consumption, greenhouse gas emissions, and material waste, supporting a sustainable industrial future. To achieve the green economy goals set within the framework of Presidential Decree PF-78 of the Republic of Uzbekistan, the phased implementation of these strategies is necessary.

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