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GENERAL PRINCIPLES OF ENERGY CONSUMPTION IN THE METALLURGICAL INDUSTRY

Abstract. *The aim of the study is to explore the theoretical foundations for improving energy consumption efficiency in the metallurgical industry under the conditions of global climate policy challenges, production transformation, and the need to reduce energy costs. The paper analyzes the main technological processes, the level of energy intensity in the industry, as well as international experience in implementing energy-efficient solutions.*

The methods. The research is based on an interdisciplinary analysis of scientific sources, industry reports, statistical data, and the techno-economic characteristics of steel production. Methods of comparative analysis of energy consumption for various technological routes and a systematic approach to assessing innovation potential are applied.

Findings. It has been established that a significant portion of energy consumption is concentrated in blast furnace–converter processes. The transition to electric arc furnace (EAF) production, the implementation of hydrogen metallurgy, the use of secondary raw materials, and digital technologies (Industry 4.0) open up opportunities for a substantial increase in energy efficiency. Examples of successful modernization at enterprises in various countries are provided

The originality. The study systematizes the factors that determine the energy intensity of production processes, reveals the relationship between technological changes and energy consumption structure, and substantiates the need for a comprehensive approach to the transformation of the industry

Practical implementation. The results can be used for strategic planning of enterprise modernization, development of energy-saving investment projects, and the formation of national industrial decarbonization policies.

Keywords: *energy consumption, metallurgy, energy efficiency, decarbonization, hydrogen, electric arc furnace, Industry 4.0, CCUS.*

Introduction

The modern development of industry is accompanied by increasing challenges in the areas of energy supply, environmental safety, and resource efficiency. In this context, the metallurgical sector-historically one of the largest energy consumers in the economy-receives particular attention due to its significant impact on the energy balance, levels of industrial greenhouse gas emissions, and the overall environmental situation. According to the International Energy Agency (IEA) [1], metallurgical production accounts for approximately 8% of global final energy consumption and about 20% of industrial energy use. The steelmaking sector alone is responsible for up to 7% of global CO_2 emissions, making it a priority target for the implementation of energy-efficient and low-carbon technologies.

Reducing the energy intensity of steel and non-ferrous metal production is a pressing issue for both developed and transition economies. The high energy demand of metallurgical processes is driven not only by the complexity of the technological cycle but also by the substantial specific requirements for thermal and electrical energy at each stage-from raw material preparation to final product rolling. Despite considerable progress in the adoption of energy-saving technologies during the second half of the 20th century, the 2000s saw a marked slowdown in the reduction of specific energy consumption, indicating that the sector is approaching the limits of efficiency achievable through conventional methods.

Current global trends in metallurgy suggest a technological transformation aimed at achieving decarbonization goals and ensuring sustainable development. Innovative approaches are gaining prominence, including hydrogen-based direct reduction of iron (H_2-DRI), electric arc furnace production using scrap metal, carbon capture, utilization and storage (CCUS), and digital solutions within the framework of Industry 4.0. The implementation of such technologies not only affects CO_2 emission levels but also significantly alters the structure and dynamics of energy consumption, introducing new requirements for energy systems and techno-economic planning.

At the same time, the energy efficiency of metallurgical enterprises is directly correlated with their competitiveness. Under conditions of high energy prices and limited access to inexpensive resources, even minor reductions in energy costs can

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yield substantial economic benefits. For Ukraine, where the metallurgical industry accounts for over 20% of industrial electricity consumption, the issue of energy modernization is particularly urgent in light of energy security, economic stability, and integration into the European energy space.

Therefore, analyzing energy consumption in metallurgy, evaluating existing technological solutions, and identifying prospects for the development of energy-efficient approaches constitute an important scientific and applied task that requires a comprehensive approach.

1. Energy Intensity of Metallurgy: Global and National Context. Steel is a fundamental building block of modern society. It is used in infrastructure, construction, household appliances, transportation, packaging, and a wide range of other products. Its unique combination of strength, durability, and recyclability makes it difficult to replace with alternative materials. Moreover, steel is relatively inexpensive and widely available. Over the past fifty years, global steel consumption has steadily increased, and, without active and coordinated efforts to reduce demand, steel consumption could rise by more than one-third by 2050 [1].

Due to its heavy reliance on energy and fossil resources, traditional steel production is highly energy-intensive and contributes significantly to carbon emissions. In 2019, the steel sector accounted for 8% of final global energy consumption and 20% of industrial energy use [1]. In 2020, the sector was responsible for 11% of global CO_2 emissions and 7% of total energy use and process-related greenhouse gas emissions [2, 3].

To meet the 1.5°C target set by the Paris Agreement and avoid the most catastrophic consequences of climate change, CO_2 emissions must be halved by the end of this decade and reach net zero by 2050. This requires an immediate reduction in greenhouse gas emissions across all sectors [4].

The steel industry, which operates one of the most energy- and carbon-intensive production processes, faces major challenges on the path to decarbonization. Research indicates that existing solutions to reduce energy consumption and substitute fossil fuels will not be sufficient to achieve the required emission reductions. Transformational change is needed, involving technologies at various stages of development [5–9].

The metallurgical industry remains among the most energy-intensive sectors of the global economy. It accounts for approximately 8% of global final energy consumption and around 20% of industrial energy use [1]. Specifically, the steel sector consumes enormous amounts of energy: in 2019, steel production was estimated to be responsible for ~7% of global CO_2 emissions, largely due to the dominance of fossil fuel-based blast furnace processes [10]. Historically, the industry has made substantial progress in improving energy efficiency - energy consumption per ton of steel has declined by approximately 60% since 1960, driven by the adoption of improved technologies and energy management practices [11].

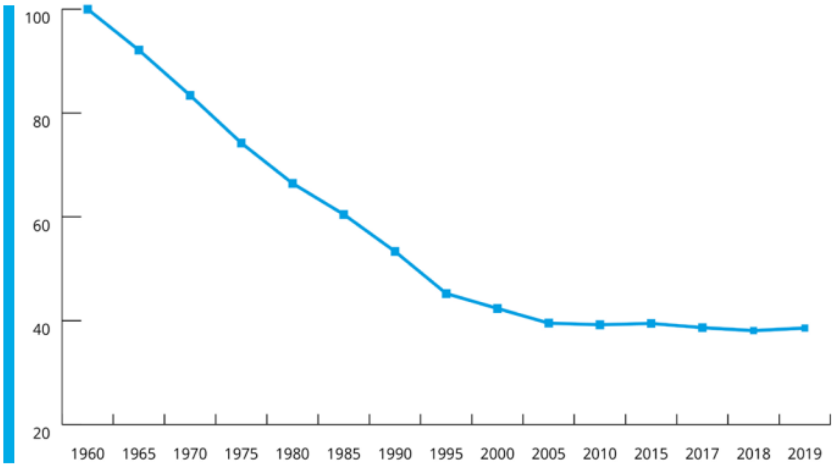

Figure 1 - Indexed global energy consumption per tonne of crude steel production [11]

The chart presented in Fig. 1 illustrates indexed global energy consumption per tonne of crude steel production from 1960 to 2019. From the 1960s to 2000, a substantial decline in energy consumption per tonne of steel is observed. This trend reflects improvements in energy efficiency, the adoption of advanced technologies, and the transition to more efficient steelmaking processes (e.g., replacing blast furnaces with electric arc furnaces). After 2000, the rate of energy reduction significantly slowed, stabilizing at around 40% of the 1960 baseline. This suggests that the industry has approached certain technological limits in reducing energy consumption. In the final segment of the chart (2015–2019), a slight increase in energy consumption is visible. This may be attributed to the increasing difficulty of achieving further improvements beyond existing efficiency levels or temporary factors such as changes in raw material inputs or production processes.

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The reduction in energy consumption per tonne of steel has been driven by several factors, including: the implementation of energy-efficient technologies in steel production; a shift toward scrap recycling in electric arc furnaces, which require less energy; improved thermal processes and the utilization of waste heat; global initiatives to reduce CO_2 emissions and improve production efficiency.

Fig. 1 demonstrates a long-term trend toward increased energy efficiency in steelmaking. However, in the near future, the potential for further reductions may be limited without breakthrough technological innovations.

Ukraine is no exception: the metallurgical industry has traditionally imposed a significant load on the national energy system. In 2020–2021, the share of metallurgical enterprises in total national electricity consumption was 23%, second only to household consumption [12]. This underscores the critical importance of energy efficiency for the national economy. At the same time, high energy intensity is also characteristic of the non-ferrous metallurgy sector - for example, producing one tonne of primary aluminum requires, on average, 14,000–17,000 kWh of electricity [13], highlighting the substantial energy demands of the industry.

Therefore, optimizing energy consumption in the metallurgical sector is a pressing task, both in terms of ensuring competitiveness and addressing energy security and environmental concerns.

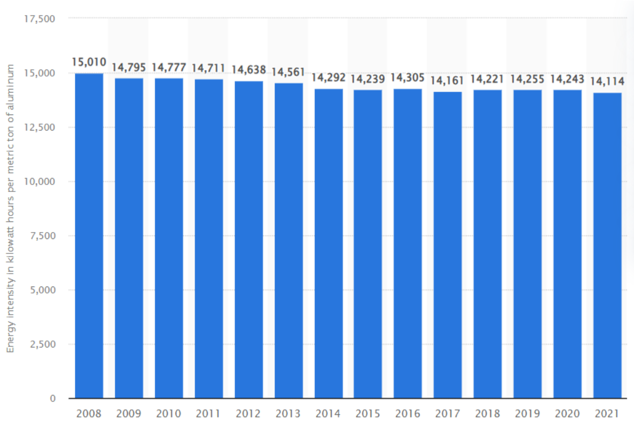

Figure 2 - Energy intensity in kilowatt-hours per metric tonne of aluminum production from 2008 to 2021 [13]

The diagram shown in Fig. 2 illustrates the trends in how, over more than a decade, the global community has sought to make aluminum production more energy-efficient. In 2008, producing one tonne of primary aluminum required 15,010 kWh of energy - a substantial amount when considering the global scale of aluminum production. However, year by year, the industry became increasingly efficient. By 2014, energy intensity had declined to 14,239 kWh, reflecting improvements in technology, optimization of production processes, and possibly the adoption of more modern equipment.

After 2015, however, the changes became less pronounced. Energy use fluctuated between 14,100 and 14,300 kWh, suggesting the approach of technological limits within conventional aluminum production methods. In 2021, the figure stood at 14,114 kWh - nearly identical to values in preceding years. This indicates that, without breakthrough innovations, further reductions in energy consumption in this sector are becoming increasingly difficult.

Thus, the chart reflects the industry's long journey toward energy efficiency - from marked progress in the early years to a gradual stabilization, signaling the limits of current technological capabilities.

2. Main Processes and Structure of Energy Consumption. Metallurgical production is characterized by a complex technological cycle, with each stage consuming a significant amount of energy. As an example, we consider the features of the blast furnace–converter process. This integrated route includes raw material preparation, pig iron production, steelmaking, and rolling operations [14]. As noted in [14], steel production is a complex technological process that requires substantial energy resources and precise control of chemical reactions. One of the most widely used steelmaking methods in the world is the blast furnace–basic oxygen furnace (BF–BOF) process, which enables the efficient conversion of iron ore into high-quality steel. This process consists of two main stages: pig iron production in the blast furnace, and its conversion into steel in the basic oxygen converter.

Blast Furnace Process. The blast furnace is a tall vertical shaft that operates continuously. Raw materials are charged from the top, and the final products (molten pig iron and slag) are discharged at the bottom. The temperature inside the furnace reaches up to 2000°C, providing the necessary conditions for the reduction of iron from the ore. To produce pig iron, the furnace is charged with three key components:iron ore (hematite Fe_2O_3 or magnetite Fe_3O_4) – the primary source of

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iron; coke (C) – serves as the fuel and reducing agent; fluxes ($CaCO_3$, dolomite) – help remove impurities and form slag. Impurities are absorbed into the slag, while molten pig iron containing 4–5% carbon accumulates at the bottom of the furnace. The hot metal is then tapped and transported to the oxygen converter for further processing.

Basic Oxygen Furnace Process .The molten pig iron produced in the blast furnace contains an excessive amount of carbon and other impurities, making it brittle and unsuitable for industrial use. To obtain steel, the carbon content must be reduced and other undesirable elements removed. This is achieved in the basic oxygen converter. The converter is a large steel vessel that tilts for charging and tapping. It is loaded with: molten pig iron (75–85%); iteel scrap (15–25%) – used to cool the melt; зure oxygen (O_2) under a pressure of 10–12 bar – the primary oxidizing agent, which burns out the impurities.

Key stages in steel production (ferrous metallurgy).

Raw material preparation: Includes agglomeration (sintering) of iron ore, pelletizing, and coal coking. These processes require thermal energy for sintering the ore concentrate and coke production. The theoretical minimum energy consumption at these stages is estimated at ~2.5 GJ per tonne of coke and ~1.0 GJ per tonne of sinter, respectively [14], thus contributing significantly to overall energy intensity.

Pig iron production:The blast furnace (BF) process relies on coke as both fuel and reducing agent. It delivers high productivity but is heavily dependent on energy from coal combustion. For example, approximately 89% of energy in the BF–BOF route comes from coke and coal, while only ~7% comes from electricity [11]. Electricity consumption in the blast furnace is relatively low - about 3–4 kWh per tonne of hot metal [15], as most of the thermal load is supplied by coke.

Steel production: The traditional BOF route utilizes the thermal energy of molten pig iron and only a small amount of auxiliary fuel, whereas the alternative electric arc furnace (EAF) route relies primarily on electricity. Electricity consumption for steelmaking in EAFs is extremely high, typically in the range of 300–400 kWh per tonne of steel [15]. By comparison, open-hearth furnaces (an obsolete technology, now rarely used) consumed ~4 kWh of electricity per tonne of steel [15], but required significant amounts of fuel, resulting in low efficiency and their replacement by modern technologies.

Rolling and finishing: Hot and cold rolling, heat treatment, etc., also require energy (mainly for billet heating, mill drives, compressors, etc.). Although their share in the total energy balance is lower, optimizing these processes (e.g., through the use of waste heat from hot metal, reduction of idle times) also yields measurable benefits.

Primary steel production from ore is significantly more energy-intensive than secondary production from scrap.

Scrap remelting in electric furnaces requires approximately eight times less energy than the full cycle from iron ore [16]. According to [1], steelmaking from scrap may require only ~12–15% of the energy compared to the ore-based route [16]. This is because the scrap-based process omits the iron oxide reduction stage - the most energy-intensive chemical step. On average, the integrated BF–BOF route consumes ~19–35 GJ per tonne of steel, while the EAF–scrap route requires ~4–7 GJ/t [17, 11].

Exact figures depend on raw material quality, product range, and plant equipment level. Factors such as ore and coke quality, steel yield from slag, and processing depth all affect specific energy consumption. Even indirect costs - such as raw material extraction and transportation - add ~6–9% to the total energy consumption per tonne of metal [11].

Thus, understanding the structure of energy consumption within the production chain allows the identification of "hot spots" - the most energy-intensive stages - and helps direct efforts toward their optimization.

3. Technologies and Energy Efficiency: International Experience. Over the past decades, the metallurgical industry has accumulated extensive international experience in implementing energy-saving technologies. Many of these are reflected in international best practice standards (Best Available Techniques, BAT) and sector-specific reference documents. Studies indicate that the application of modern energy-efficient technologies could reduce steelmaking energy consumption by approximately 20% compared to the global average, if production worldwide were

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brought to the BAT level [17]. Half of this improvement potential lies in countries with traditionally higher specific energy consumption - notably China [17].

Key directions for improving energy efficiency include:

Utilization of Secondary Energy Resources. Modern integrated steelworks widely implement waste heat and process gas recovery systems. For instance, blast furnace and converter gases are used for electricity generation or hot blast heating; cogeneration units are installed; coke dry quenching (CDQ) systems are employed to reclaim heat from hot coke; and top-pressure recovery turbines (TRT) are used in blast furnaces. These measures help utilize fuel energy more efficiently and reduce dependency on external energy sources. According to the World Steel Association, up to 60–75% of the energy contained in blast furnace and coke oven gases can be recycled back into the process or used to generate electricity instead of being lost [11].

Equipment and Process Modernization. Transitioning to advanced units - such as furnaces with regenerative burners, more efficient oxygen injection systems, or the replacement of open-hearth furnaces with converters or electric arc furnaces - results in substantial energy savings per tonne of product. For example, the global phase-out of obsolete open-hearth furnaces has eliminated their characteristic low efficiency. In contrast, modern electric arc furnaces (EAFs) equipped with advanced control systems have achieved high productivity with reduced heat losses. Likewise, the implementation of continuous casting instead of multi-stage ingot rolling has significantly reduced the need for reheating, leading to fuel savings.

Energy Management and Digital Technologies (Industry 4.0).Many plants operate automated energy management systems (EMS), which monitor and optimize energy consumption in real time [11].The use of sensors, big data, and artificial intelligence allows for improved control of furnaces, compressors, rolling mills, and other equipment, minimizing idle periods and peak loads. In the EU, there are documented cases where digitalization led to over 30% improvements in energy efficiency in specific production areas [18]. While the full impact of Industry 4.0 is still being researched, the trend is clear: "smart" factories are capable of using energy more rationally, reducing both consumption and emissions.

Other Measures. These include improvements in thermal insulation and the use of modern materials (e.g., more durable refractories that reduce heat losses); recovery of heat from cooling systems; implementation of high-efficiency electric motors and variable frequency drives for mechanical systems, among others. Together, these steps contribute to establishing a culture of energy conservation within enterprises. Such measures often offer relatively short payback periods and are supported by international energy efficiency programs.

International experience clearly demonstrates the effectiveness of these approaches. In developed countries (e.g., Japan, South Korea, and the EU), the energy intensity of steel production is now approaching theoretical limits, thanks to widespread implementation of BAT. In contrast, developing countries show a broader performance range but are undergoing active modernization - especially China, which accounts for ~50% of global steel output. Notably, more than half of the world’s energy-saving potential in steelmaking is concentrated in China [17], which stimulates international technology transfer projects and investments in upgrading steelmaking capacities.

The Ukrainian steel industry is also adopting energy-efficient solutions. In recent years, several projects have been implemented, including process gas recovery, modernization of rolling mills, and installation of more efficient boilers and heaters at multiple plants. Thus, the global trend towards improved energy efficiency also extends to the national level, as reflected in recent publications and studies by Ukrainian researchers over the past five years.

4. Low-Carbon Technologies and Their Impact on Energy Consumption. Contemporary climate policy challenges are driving a technological transformation in the metallurgical industry aimed at decarbonization. These emerging technologies affect not only CO_2 emission levels but also the structure and volume of energy consumption. International experience outlines several key pathways: transitioning to hydrogen as a reducing agent, electrification of processes, the use of biomass, and carbon capture and storage/utilization (CCS/CCUS).

Each of these pathways has distinct energy and economic characteristics:

Hydrogen-Based Direct Reduction (H_2-DRI). Direct reduction technologies using hydrogen instead of natural gas or coke are gaining momentum (notable EU

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projects include HYBRIT, H2FUTURE, among others). Hydrogen enables near-complete elimination of CO_2 emissions at the iron ore reduction stage. However, hydrogen production-especially green hydrogen via electrolysis-requires vast amounts of electricity. Studies predict that switching from traditional sinter–blast furnace technology to H_2-DRI and electric arc furnace (EAF) steelmaking would lead to a dramatic increase in electricity consumption. Specifically, Ukrainian researchers estimate that producing 10 million tonnes of steel per year would raise electricity demand from approximately 2.74 to 35.13 billion kWh (a 12.8-fold increase) under a full H_2-DRI + EAF scenario compared to the conventional BF–BOF route [19–21]. Correspondingly, required electrical capacity would surge from ~0.5 GW to 6.15 GW [19]. This presents a massive challenge for energy infrastructure, though it is accompanied by a substantial reduction in greenhouse gas emissions - approximately 2.6 times lower (from ~18 million tonnes to 7 million tonnes of CO_2 per 10 million tonnes of steel) [19]. In the long term, coupling hydrogen-based metallurgy with renewable electricity generation could enable near-zero emissions, although it raises critical issues of generation stability (solar, wind) and energy storage. International pilot projects in Sweden and Germany confirm the technical feasibility of this route, although its economic viability remains under debate.

Scrap-Based Electric Arc Furnace (EAF) Production. Increasing the share of scrap in the raw material mix is one of the simplest ways to reduce both energy consumption and emissions. As previously noted, scrap melting requires approximately one-eighth of the energy compared to ore-based steelmaking [16] and involves minimal use of fossil carbon. As a result, many countries are expanding their EAF capacity; globally, this route accounted for over 26% of total steel production in 2020 and continues to grow. In countries like the USA, Italy, and Turkey, the majority of steel is produced from scrap. In Ukraine, the BF–BOF route has historically dominated, but recent years have seen the commissioning of new EAFs (e.g., at Interpipe Steel in 2012), reflecting the global trend. Expanding EAF-based steelmaking reduces overall primary energy demand but increases electricity consumption - necessitating corresponding development of power grids and generation capacity.

Fossil Fuel Substitution. Partial replacement of coke and natural gas with alternative energy sources is already being tested. One avenue involves using biomass (biocoke, charcoal) in blast furnaces and sintering. Some European blast furnaces now include a certain percentage of biocarbon in the burden, which reduces the fossil carbon input. The impact on the energy balance is relatively modest (the calorific value of biomass is similar to coal), but scale is limited by biomass availability. Another approach involves integrating renewable electricity into thermal processes - for example, using plasma heaters for hot blast generation or electrolyzers for reagent production. While these auxiliary technologies do not drastically lower energy consumption, they help reduce the carbon footprint.

Carbon Capture, Utilization, and Storage (CCUS).CCUS technologies can be applied at metallurgical facilities to capture CO_2 from blast furnace or converter gases. While they do not reduce energy consumption per se - and in fact slightly increase it due to energy requirements for CO_2 capture and compression - they offer a pathway to drastically cut emissions in processes where eliminating coke use is not yet feasible [23]. Implementing CCS at a steel plant may require an additional ~1–2 GJ of energy per tonne of steel, which must be accounted for in economic assessments. Some projects explore the conversion of captured CO_2 (CCU), for instance into synthetic fuels (e.g., methanol) or its use in the food industry [23]. These applications may generate byproducts and partially offset costs, although such schemes are still at an early development stage.

Overall, low-carbon technologies in metallurgy often lead to increased electricity intensity of processes. Steel is produced with less fossil fuel input, but requires more electricity and capital investment. Therefore, it is critical to assess these innovations comprehensively - considering the availability of affordable low-carbon electricity, grid capacity, and economic incentives (e.g., emission allowances, CO_2 taxes). International experience currently shows that EU countries, Japan, and South Korea are prioritizing hydrogen and EAF expansion, China is actively experimenting with CCUS technologies and increasing scrap use, while the USA and other developed economies already operate with high shares of electric steel and continue improving the energy efficiency of this route.

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5. Economic Aspect of Energy Consumption. The cost of energy is a critical factor in determining the competitiveness of the metallurgical industry. According to the World Steel Association, energy carriers account for 20–40% of the total production cost of steel [11]. Therefore, even a modest improvement in energy efficiency directly reduces production expenses and increases profitability. Enterprises implementing energy-saving projects can achieve substantial savings: in many cases, such measures have a payback period of only 1–3 years due to reduced fuel and electricity bills. Furthermore, energy efficiency is closely linked to environmental charges - lower fuel consumption results in lower CO_2 emissions and, consequently, reduced expenditures on emission allowances or carbon taxes under environmental regulations.

Global energy prices significantly influence the steel industry. The years 2021–2022 were particularly challenging for the European sector: a sharp increase in natural gas and electricity prices led to the shutdown of some steelmaking capacities in the EU [24]. For instance, in autumn 2022, energy costs for certain plants escalated to the point where their monthly energy bills equaled those of entire previous years [24]. Companies were forced to reduce steel output to 50% of capacity or temporarily halt electric arc furnaces [24]. This triggered a supply crisis in the steel market and increased the EU’s dependence on imports [24]. Hence, extremely high energy prices can pose an existential threat to the steel industry, even in developed economies.

In Ukraine, the war and attacks on energy infrastructure in 2022 also caused an electricity shortage, forcing steel plants to temporarily shut down or operate under consumption quotas while implementing strict energy-saving regimes [12]. These extreme situations highlight the importance of a stable energy supply and the need for production flexibility in response to price shocks.

Investments in energy efficiency and new technologies require substantial capital but pay off in the long run through cost savings and “green” incentives. According to Chinese researchers, by 2030, technical measures aimed at improving energy efficiency in China’s steel industry will cost, on average, ~27 yuan per tonne in terms of emission reduction, whereas transitioning to new production structures (e.g., mass deployment of electric or hydrogen-based steelmaking) could cost up to ~703 yuan per tonne in marginal abatement costs [25]. The high capital intensity of new technologies is a major barrier to their implementation [25]. For this reason, many companies and countries adopt a phased approach to decarbonization: first implementing the most cost-effective energy efficiency measures, and only then moving on to expensive transformational projects. Economic analysis suggests that without additional incentives (such as low-interest loans, subsidies, or carbon market revenues), businesses may postpone the adoption of radical new technologies [25]. The inclusion of metallurgy in emissions trading systems and the tightening of environmental requirements aim to rebalance this situation by making energy-efficient and low-carbon technologies more economically viable.

At the same time, energy management is becoming an integral part of the business strategy in metallurgical companies. Enterprises are adopting ISO 50001 standards, developing portfolios of energy-saving projects, and assessing their profitability. Some Ukrainian researchers propose methods for managing such projects and adaptive energy consumption planning at industrial plants [26, 27], enabling scientifically grounded investment decisions in energy efficiency. Energy saving is thus viewed not only as a means of reducing costs but also as a way to mitigate price volatility risks and comply with environmental standards.

In conclusion, energy consumption in metallurgy is not only a technical challenge but also an economic one: optimal energy management has a direct impact on the financial performance and resilience of enterprises.

Conclusions

A review of the literature from the past five years indicates that energy consumption in the metallurgical industry remains a central focus for researchers and practitioners alike. As one of the most energy-intensive sectors, the industry faces a dual challenge - improving energy efficiency to reduce costs while simultaneously undergoing a transformation to lower its carbon footprint.

International experience demonstrates substantial progress in the deployment of energy-efficient technologies - ranging from waste heat recovery and equipment modernization to digital control systems. As a result, specific energy consumption for conventional steel production has been significantly reduced. In parallel,

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research and pilot implementations of breakthrough technologies - such as hydrogen metallurgy (H_2-based processes), ore-based electric smelting, and carbon capture, utilization, and storage (CCUS) - are laying the groundwork for a future shift in the industry's energy balance toward electrification and renewable energy sources.

These changes are already having a tangible impact: new demands are emerging for power systems (e.g., the provision of large volumes of "green" electricity), cost structures at enterprises are evolving, and a new economic model for metallurgy is taking shape - one in which the kilowatt-hour becomes as critical a resource as iron ore or coal.

Ukrainian and international publications consistently emphasize that enhancing energy efficiency is key to strengthening the competitiveness of the metallurgical industry in the global market [11], while reducing energy dependence is essential to ensuring its resilience in the face of external shocks.

In conclusion, the sustainable development of the metallurgical sector is unattainable without the optimization of energy consumption - both through the adoption of advanced technologies and the implementation of sound economic policy and international cooperation in this domain.

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ЗАГАЛЬНІ ЗАСАДИ ЕНЕРГОСПОЖИВАННЯ В МЕТАЛУРГІЙНІЙ ПРОМИСЛОВОСТІ

Абстракт. *Метою роботи є дослідження теоретичних основ підвищення ефективності енергоспоживання в металургійній промисловості в умовах глобальних викликів кліматичної політики, трансформації виробництва та необхідності зниження енергетичних витрат. Проаналізовано основні технологічні процеси, рівень енергоємності галузі, а також міжнародний досвід упровадження енергоефективних рішень.*

Методика. Дослідження базується на міждисциплінарному аналізі наукових джерел, галузевих звітів, статистичних даних та техніко-економічних характеристик виробництва сталі. Використано методи порівняльного аналізу енерговитрат для різних технологічних маршрутів, а також системний підхід до оцінки потенціалу інновацій.

Результати. Встановлено, що значна частина енергоспоживання припадає на доменно-конвертерні процеси. Перехід до електропічного виробництва, впровадження водневої металургії, використання вторинної сировини та цифрових технологій (Industry 4.0) відкриває шляхи до істотного підвищення енергоефективності. Наведено приклади успішної модернізації на підприємствах різних країн.

Наукова новизна. У роботі систематизовано фактори, що визначають енергоємність виробничих процесів, розкрито взаємозв'язок між технологічними змінами та структурою енергоспоживання, обґрунтовано необхідність комплексного підходу до трансформації галузі.

Практичне значення. Результати можуть бути використані для стратегічного планування модернізації підприємств, розробки інвестиційних проєктів з енергозбереження та формування національної політики декарбонізації промисловості.

Ключові слова: *енергоспоживання, металургія, енергоефективність, декарбонізація, водень, електропіч, Industry 4.0, CCUS.*

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