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ENERGY EFFICIENCY IN THE METALLURGICAL SECTOR: CONCEPT AND EVALUATION METRICS

Abstract. *The aim of the study is to provide an analytical synthesis of the theoretical foundations and practical approaches to improving energy consumption efficiency in the metallurgical industry, taking into account modern challenges of climate policy, rising energy prices, the need for decarbonization, and the economic feasibility of production process modernization.*

The methods. The research is based on an interdisciplinary analysis of scientific publications, international reports, statistical data, and techno-economic characteristics of steel production. Structural-comparative methods of analyzing energy consumption across different technological routes were applied, along with a systematic approach to assessing innovation potential and international benchmarking practices.

Findings. The study identifies the main factors contributing to energy intensity in metallurgy and substantiates the technological reserves for improving efficiency, including the transition to electric arc furnace (EAF) steelmaking, the use of secondary raw materials, waste heat recovery, implementation of cogeneration, digitalization, and hydrogen-based metallurgy. Examples of successful modernization and national support programs from leading countries are also presented.

The originality. The paper systematizes current energy efficiency indicators and production routes in steelmaking, characterizes the impact of various technological strategies on integrated energy intensity, and proposes criteria for assessing energy-saving potential at both macro and micro levels.

Practical implementation. The results can be used to substantiate enterprise energy strategies, shape industrial decarbonization policies, prepare investment projects, and support the development of national and international programs to improve energy efficiency in the metallurgical sector.

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

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Introduction

The metallurgical industry plays a key role in the development of infrastructure, mechanical engineering, energy, and other strategically important sectors of the economy. At the same time, metallurgy is one of the most energy-intensive and resource-dependent industrial activities, placing high demands on effective energy consumption management. As of the early 21st century, the metallurgical sector accounts for approximately 8% of global final energy consumption and more than one-fifth of industrial carbon dioxide emissions [1]. Over the past two decades, global steel production has doubled, leading to a corresponding increase in energy consumption and environmental pressure.

The issue of energy efficiency in metallurgy arises not only as a matter of resource conservation, but also as a factor determining the competitiveness of enterprises in the global market. The specific energy consumption per tonne of steel remains significant, particularly in countries where traditional blast furnace–converter production dominates. In contrast, countries that have prioritized electric arc furnace (EAF) production and scrap-based recycling demonstrate significantly lower energy intensity indicators.

Current trends require not only local optimization of technologies but also a systemic transformation of metallurgical production in line with the principles of sustainable development and decarbonization. The implementation of energy-efficient solutions - from cogeneration and waste heat recovery to digital control technologies and the use of hydrogen as a reducing agent - is regarded as a necessary condition for technological modernization of the sector. In recent years, special attention has been paid to assessing steel production routes based on specific energy consumption. According to estimates by international organizations, the potential for energy savings at existing plants is up to 20% through the application of Best Available Techniques (BAT). Moreover, the transition to EAF production using steel scrap can reduce energy consumption by 60–70% compared to conventional ore-based routes.

At the same time, the industry remains highly heterogeneous: leading countries such as the EU members, Japan, the USA, and South Korea have achieved high energy efficiency through intensive investment in modernization and strong government support. Meanwhile, metallurgical enterprises in developing countries or those with outdated production bases continue to operate with higher fuel and electricity consumption.

For Ukraine, as for many other countries with a high share of blast furnace production, energy efficiency is a doubly relevant issue - it is directly linked to production costs, access to international markets, and compliance with environmental legislation. In the context of post-war recovery, Ukraine has a unique opportunity to make a technological leap, moving from outdated energy-intensive schemes to modern digitalized and “green” solutions.

In this regard, the analysis of current technological trends, systematization of energy efficiency assessment approaches, and study of international experience in metallurgical innovation become particularly relevant. The successful implementation of such measures will not only reduce energy consumption but also improve economic efficiency, lower greenhouse gas emissions, enhance energy security, and align production with the principles of the circular economy.

The metallurgical industry is among the most energy-intensive sectors: it accounts for around 8% of global final energy use [1] and approximately 21–24% of industrial CO_2 emissions [2]. Steel production is especially energy-demanding - energy and raw materials constitute up to 60–80% of production costs [3]. Over the past 20 years, global steel output has doubled [4], resulting in equivalent increases in energy use and emissions. Despite a certain decline in energy intensity, these improvements lag behind the growing demand [5].

Studies show that since 1900, the specific energy consumption per tonne of steel has decreased by approximately 67%, mainly due to process efficiency gains [6]. However, since the mid-1990s, the pace of global energy efficiency improvements has plateaued - particularly due to the rapid expansion of production in countries with less efficient technologies [6].

Therefore, energy efficiency in metallurgy is currently a priority from both economic (cost reduction) and environmental (GHG mitigation) perspectives. This paper provides an analytical overview of key energy efficiency indicators in metallurgy, modern technologies for improving energy performance, and international experience in implementing such solutions in the sector.

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1. Key Indicators of Energy Efficiency in Metallurgy. The primary integral indicator of energy efficiency in the metallurgical sector is the specific energy consumption per unit of output, typically expressed in gigajoules per tonne of crude steel produced (GJ/t). Over the past decades, the global steel industry has made significant progress: according to the World Steel Association, due to the implementation of energy-saving technologies, the average energy consumption per tonne of steel has decreased by approximately 60% compared to 1960 levels [10].

As of the mid-2010s, the global weighted average energy intensity of steel production was estimated at approximately 17.6 GJ/t [7, 8]. This figure varies significantly depending on the technological route and the country. For example, countries with a high share of electric arc furnace (EAF) production demonstrate lower average energy intensity: Italy and Spain recorded some of the lowest values globally, while China had one of the highest [7].

The key reason for this difference lies in the proportion of scrap-based steel production: in Italy and Spain, a large share of steel is produced in electric arc furnaces, whereas in China, blast furnace–converter production still predominates [7, 8].

Global steel production more than doubled between 2000 and 2018 (see Fig. 1).

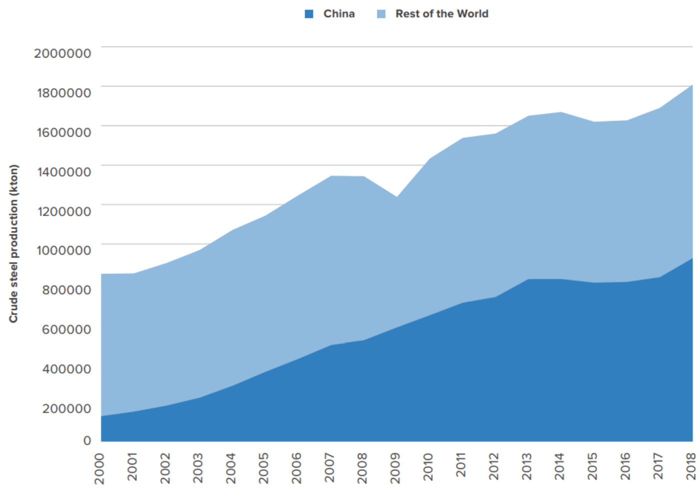

Figure 1 – Crude steel production in China and the rest of the world, 2000–2018 (Source: World Steel Association 2018 [8], 2019a [9])

The chart presented in Fig. 1 illustrates the dynamics of crude steel production in China and the rest of the world over the period from 2000 to 2018. Its structure clearly demonstrates both the significant growth in global steel output and the substantial change in China's role within the industry. In 2000, total steel production was just over 800 million tonnes, with China representing only a small share of the global volume. However, from the early 2000s onward, China experienced a rapid increase in steel production. Its share in total output grew significantly as a result of intense industrialization and urbanization. Between 2000 and 2007, global steel production rose steadily, reflecting a general period of global economic expansion. In 2008, however, a sharp decline occurred, coinciding with the global financial crisis. This drop in steel production was mainly observed in the rest of the world, while China continued to grow, albeit at a slower pace. After 2009, global steel production recovered relatively quickly, with China contributing the most to this rebound. By 2014, China's steel production had increased to over 800 million tonnes, while output in the rest of the world remained approximately stable.

The noticeable decline in 2014 may be linked to an economic slowdown in China and to government measures aimed at curbing overcapacity and shutting down outdated or illegal production facilities. Nevertheless, China resumed gradual growth, and by 2018, total global steel production exceeded 1.8 billion tonnes. Several important conclusions can be drawn from the chart. First, China has become the undisputed leader in steel production, with a decisive influence on the global metallurgical industry. Second, global steel production is highly sensitive to economic cycles, as clearly seen during the downturns of 2008 and 2014. Finally, although the rest of the world shows moderate growth, its pace is significantly slower than that of China, highlighting China's dominant role in global steel output. In 2018, China accounted for 51% of global steel production, compared to just 15% in 2000. The 2008 decline in production was caused by the global economic recession. The 2014 downturn was primarily due to the deceleration of China's economic growth and chronic overcapacity, which led to the closure of illegal induction furnaces and outdated steel mills in the country. For instance, in the United States, approximately 70% of steel is produced using electric arc furnaces, resulting in an average energy intensity about one-third lower than that of China.

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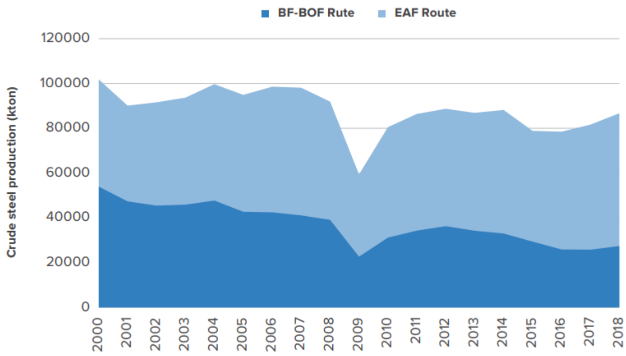

Figure 2 – Crude steel production in the United States by production routes, 2000–2018: (Source: World Steel Association 2018 [8], 2019a [9])

Throughout the period from 2000 to 2018, crude steel production in the United States underwent significant changes, as illustrated in Fig. 2. Already at the beginning of the 2000s, it was evident that the U.S. steel industry relied on two primary production routes: the blast furnace–basic oxygen furnace (BF–BOF) route and the electric arc furnace (EAF) route.

While both processes were actively used, the traditional BF–BOF method initially accounted for a larger share of production, gradually giving way to the more modern EAF process.

In the early years of the study period, steel production remained relatively stable at around 100 million tonnes per year. However, in 2008, a major turning point occurred that affected not only the U.S. steel sector but the global economy as a whole - the global financial crisis. Demand for steel dropped sharply, leading to a dramatic reduction in output.

The BF–BOF segment was particularly affected, as it requires substantial capital investment and involves longer production cycles. During this time, U.S. steel production fell to its lowest level in two decades.

Nevertheless, like many other industries, steelmaking began to recover gradually. Starting in 2010, production increased again, although pre-crisis levels were not fully restored. However, this period marked a turning point in the structural transformation of the industry. An increasing number of facilities began transitioning to electric arc furnaces (EAF), which are more flexible, economically advantageous, and environmentally friendly. It was primarily through this method that the U.S. steel industry managed to recover, albeit at a slightly lower production level compared to the early 2000s.

In the final years of the analyzed period - from 2015 to 2018 - the industry entered a relatively stable phase once again. The BF–BOF route continued to lose ground, while EAF technology steadily established itself as the dominant production method. This shift mirrored global trends in the steel industry, as companies favored technologies that allowed faster adaptation to market fluctuations.

Key indicators also include specific fuel consumption by production route and energy efficiency (conversion efficiency). Primary steel production (from ore) is carried out mainly via the blast furnace–basic oxygen converter route (BF–BOF) or through direct reduced iron (DRI) followed by melting in an electric arc furnace (DRI–EAF).

Secondary steel production involves remelting scrap in EAFs. These routes differ significantly in terms of energy intensity. The BF–BOF route consumes on average ~18–20 GJ per tonne of steel, most of which is derived from coking coal. In contrast, the EAF scrap-based route requires several times less energy. According to estimates, steelmaking from scrap uses only ~1/4 to 1/3 of the energy compared to ore-based production [10].

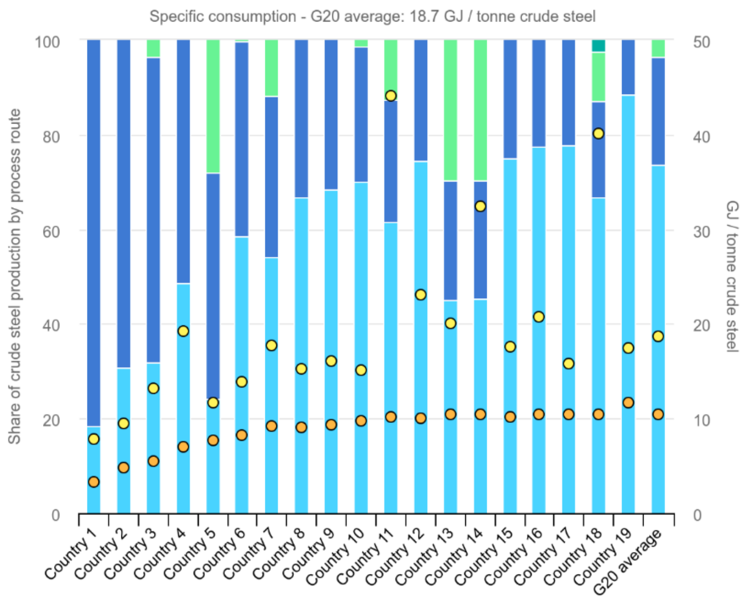

Figure 3 – Final energy consumption and energy intensity under Best Available Technologies (BAT), 2018

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The chart presented in Fig. 3 illustrates the final energy consumption and energy intensity of crude steel production across various G20 countries in 2018. It highlights the extent to which different steelmaking technologies are utilized and how much energy is consumed per tonne of finished steel.

On the left vertical axis, the chart shows the share of steel production by technological route, while the right vertical axis indicates energy consumption in gigajoules (GJ) per tonne of steel. Each bar consists of differently colored segments representing various steelmaking processes. Yellow dots indicate the average energy intensity for each country.

The main conclusion from the chart is that both the structure of steel production and the level of energy intensity vary significantly between countries. Some countries lead in the use of energy-efficient technologies, while others continue to rely on more traditional but less efficient methods.

Steel production is one of the key industrial sectors, but it is also among the most energy-intensive. This chart clearly demonstrates the wide disparity in energy consumption across G20 countries in 2018, and how the applied technologies impact production efficiency.

As noted in sources [10–13], different countries employ different production routes. In some, electric arc furnace (EAF) steelmaking dominates - a process that allows for significant energy savings. In others, the conventional basic oxygen furnace route (BF–BOF) still prevails, which requires substantially more energy. This explains the considerable variation in energy intensity, represented by the yellow dots. In some countries, these indicators are below the G20 average of 18.7 GJ per tonne of steel, while in others they exceed this threshold significantly.

One of the most notable observations is the clear distinction between countries that have adopted advanced technologies and those that continue to rely on outdated production methods. Nations that have invested in modernization are already reaping the benefits of reduced energy consumption and, accordingly, lower production costs. Meanwhile, countries that remain heavily dependent on traditional blast furnace routes consume more energy resources, making their steel industries less competitive in the modern market.

The chart also hints at emerging trends. It is becoming increasingly evident that the steel industry is moving toward more energy-efficient solutions. While in some countries the EAF route already dominates, over the coming decades this method may largely replace traditional steelmaking approaches. In addition to economic benefits, this shift also reduces the environmental impact of production.

Secondary steelmaking can save up to 60–70% of energy per tonne [13] - and by some estimates, even as much as 1/8 of the energy required for primary production [14]. In practice, all new steel contains a certain percentage of scrap (in basic oxygen converters, up to ~30% of the charge may be scrap metal) [13], but the key factor for energy efficiency at the sector level is the share of EAF-based production.

Currently, approximately 25% of global steel is produced using electric arc furnaces [10], while around 75% still relies on the more energy-intensive blast furnace route. Thus, increasing the share of EAF production represents one of the main energy efficiency reserves for the industry as a whole.

At the same time, energy performance also depends on the technology level at each production stage. For instance, Best Available Technologies (BAT) offer energy consumption levels of approximately 14.8 GJ/t for the BF–BOF route and about 2.6 GJ/t for scrap-based EAF (thin-slab route), according to estimates by Lawrence Berkeley National Laboratory [15]. Comparing actual national indicators to BAT benchmarks helps assess the potential for efficiency improvement. According to international benchmarking, many G20 countries still have the economic potential to reduce energy use in steel production by 10–20%, approaching BAT performance levels [12].

Therefore, key metrics for monitoring energy efficiency in metallurgy include: specific fuel and electricity consumption per tonne (by production route); share of secondary (scrap-based) steelmaking; composite efficiency index relative to global best practices.

2. Modern Energy-Efficient Technologies in Metallurgy**.** Reducing energy consumption in the metallurgical industry is achieved through both equipment modernization and the implementation of new processes and control systems. The following are key technological directions for improving energy efficiency at steel plants:

ISSN-print 1991-7848
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Waste Heat Recovery and Cogeneration.A significant portion of heat in the metallurgical cycle is released through process gases and hot materials. Modern plants implement heat recovery systems to convert this thermal energy into useful energy. For example, by-product gases from blast furnaces and coke plants are redirected from flare stacks to steam and electricity production, covering over 60% of internal energy needs at integrated works [10]. Many integrated steelworks operate their own combined heat and power (CHP) plants fueled by blast furnace and coke oven gas, simultaneously generating both electricity and process steam/hot water. This cogeneration significantly improves overall fuel utilization efficiency: modern CHP systems achieve 65–80% efficiency, compared to approximately 50% for the combined efficiency of separate power and steam generation [16].

Among the most effective heat recovery technologies is coke dry quenching (CDQ), where incandescent coke is quenched not with water but with inert gas, allowing for heat extraction to generate steam. Another proven solution is top-pressure recovery turbines (TRT) installed on blast furnaces, where the energy of pressurized exhaust gas is converted into electricity. These technologies are standard on nearly all modern Japanese blast furnaces and are widely used across the EU and China [17].

Additionally, waste heat from sintering machines, steelmaking furnaces, and rolling mills is increasingly recovered via heat exchangers for secondary applications (e.g., air or water preheating, steam production, or electricity generation via organic Rankine cycle). Collectively, heat recovery systems can reduce specific fuel consumption by 10–20% and yield substantial cost savings. Many such solutions offer short payback periods: according to U.S. DOE energy audit programs, most energy-saving recommendations in steel plants pay back within 2 years, and nearly 40% within 9 months [18]. This explains why waste heat recovery and cogeneration have become standard practices at modern steelworks - not only enhancing efficiency but also providing rapid economic returns.

Energy-Efficient Steelmaking Processes. The stark contrast in energy consumption between the traditional blast furnace route and scrap-based steelmaking has driven significant technological shifts. Electric arc furnaces (EAFs) are now considered a key energy-efficient technology, particularly when combined with scrap usage. The complete production cycle for one tonne of steel in EAFs consumes on average 60–70% less energy than the BF–BOF route [11]. This is confirmed by practice: countries with a high share of EAF-based steel production (e.g., Turkey, USA) achieve substantially lower energy intensity at the sectoral level [18].

However, the EAF method is constrained by the availability of scrap, which is not unlimited (globally, ~85% of generated scrap is collected) [20]. Thus, primary iron production remains essential to meet demand.

To improve the efficiency of primary ironmaking, technologies such as direct reduced iron (DRI) using natural gas or hydrogen instead of coke are being implemented. The DRI process followed by melting in EAFs offers a partial replacement for blast furnace production. Its energy efficiency depends on the type of fuel: with natural gas, the specific energy consumption can be slightly lower than that of the BF–BOF route, although overall DRI–EAF typically still consumes ~16–18 GJ/t (only slightly less than BF–BOF) [15]. The main advantage of DRI is the reduction in CO_2 emissions when using gas or hydrogen, which is why many Middle Eastern countries with cheap gas have adopted this route (e.g., historically, ~100% of Egypt's steel has been produced via DRI–EAF) [15].

For the blast furnace process, key energy efficiency improvements include modernization of furnaces and auxiliary equipment: pulverized coal injection (PCI) to replace part of the coke, use of maximum-temperature hot blast, cleaning and recycling of blast furnace gas, and more efficient stove heaters.

Modern blast furnaces in Japan and South Korea have reached such high levels of thermal efficiency that further energy reductions are approaching theoretical limits [20]. Thus, in the long term, breakthrough technologies - such as hydrogen-based reduction, electric melting of iron ore pellets, or plasma/electrolytic methods - are seen as pathways to radically improve energy efficiency and decarbonize the industry [20].

These technologies are currently in the pilot or demonstration phase, with commercial deployment expected closer to the 2030s [20]. Therefore, in terms of currently available solutions, metallurgical companies are focusing on maximizing

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scrap usage, transitioning to EAFs where possible, and modernizing existing BF facilities to meet the highest global energy efficiency standards.

Digitalization and Energy Management Systems.In recent years, significant attention has been paid to the use of digital technologies to optimize energy use in industry. Steel plants are implementing monitoring and control systems that track real-time operating parameters of furnaces, rolling mills, motors, and other energy consumers. Advanced software solutions - Advanced Process Control (APC), digital twins, artificial intelligence - allow precise process control, minimizing non-productive fuel and electricity losses [21].

For example, AI models can optimize the thermal regime of electric arc or blast furnaces to reach the target temperature with minimal coke or electricity use. In Europe, several initiatives support the digital transformation of metallurgy. Notably, in 2024, the DIGREEs project was launched with EU support. This collaboration among 12 partners (research institutions and steel manufacturers) aims to develop a digital platform with networked sensors and AI to optimize the full production cycle - from raw material preparation to rolling [21].

The introduction of digital twins and control models at European steel plants is expected to deliver up to €800 million in annual energy cost savings and reduce CO_2 emissions by 6 million tonnes per year in the medium term [21].

Beyond targeted projects, many companies are already implementing Industry 4.0 elements: energy dispatch systems, predictive analytics for equipment (to prevent failures and downtime), optimization of operating schedules to flatten peak loads, etc.

A critical component of this transformation is the adoption of Energy Management Systems (EnMS) in line with ISO 50001. As noted by the IEA, formalized energy management ensures continuous application of best practices at relatively low cost [11]. ISO 50001–certified companies regularly analyze their energy consumption, monitor Energy Performance Indicators (EnPIs), and develop energy efficiency plans - enabling identification of new saving opportunities.

In combination, digital solutions and energy management systems can deliver an additional 5–10% reduction in specific energy consumption by fine-tuning processes and eliminating losses. Therefore, digitalization is emerging as a crucial technological driver of energy efficiency, effectively complementing hardware modernization efforts.

3. International Experience in the Implementation of Energy-Efficient Technologies. Decades of experience from the world’s leading steel-producing countries demonstrate that improving energy efficiency is a mutually beneficial process - it reduces production costs while simultaneously supporting environmental goals. Developed nations have already made significant progress in reducing specific energy consumption, yet improvement potential remains across nearly all regions [11]. According to the IEA, implementing currently available energy-efficient technologies across global steel plants could save up to ~20% of energy per tonne of steel on average [11].

Below is an overview of selected country experiences and global initiatives:

Japan has traditionally been a global leader in energy efficiency in the steel industry. Since the oil crisis of the 1970s, Japanese steelmakers have systematically implemented energy-saving innovations - from comprehensive gas and heat recovery systems to advanced blast furnace technologies. As a result, Japan's steel plants have achieved the highest energy efficiency worldwide [22]. As early as the 2010s, Japan announced its intention to improve steel production efficiency by 35% by 2030 compared to baseline levels - underscoring its ambition to push efficiency boundaries even further [23].

To share best practices, Japan launched a global energy efficiency benchmarking program during its G20 presidency in 2019 [11]. In cooperation with the IEA, an international methodology was developed to compare specific energy consumption per tonne of steel, accounting for differences in production structures. Findings revealed that many countries could significantly reduce their performance gaps through process optimization and the implementation of Best Available Techniques (BAT) [11]. Japanese companies are also active in technology transfer: through joint implementation mechanisms and partnerships, they support the installation of heat recovery systems, advanced tuyères, and automation systems at plants in China, India, and ASEAN nations.

The European Union emphasizes energy efficiency through regulatory and financial mechanisms. The EU Energy Efficiency Directive (EED) obliges member

ISSN-print 1991-7848
ISSN-online 2707-9457

states to promote industrial efficiency, including mandatory energy audits for large enterprises and support for high-efficiency cogeneration [24]. Sector-specific BAT Reference Documents (BREFs), such as the "Iron & Steel BREF," define technical options for minimizing energy use, which are gradually implemented at EU steelworks.

Many European plants have undergone modernization with support from public funding programs (e.g., Horizon 2020, Innovation Fund), co-financing installations of energy-efficient equipment. Technologies such as coke dry quenching (CDQ), regenerative burners in reheat furnaces, and variable frequency drives for rolling mill motors are widely used. Countries like Germany and France also support digitalization projects (e.g., DiGreeS) aimed at reducing energy consumption. As a result, the energy intensity of European steel is among the lowest globally. For example, the average steel plant in Germany or Italy consumes far less energy per tonne than a typical Chinese facility, largely due to a higher EAF share and BAT adoption [25]. Furthermore, the EU continues to promote fuel switching and electrification/hydrogen-based technologies under the Green Deal and industrial decarbonization programs.

The United States has a different production structure, with a dominance of mini-mills using scrap-based EAFs. As of recent years, about 70% of U.S. steel is produced in EAFs, resulting in a lower sectoral average energy intensity (placing the U.S. among the global top 5 performers) [17]. The U.S. government has historically supported energy efficiency through the Department of Energy (DOE) programs. In the 2000s, the Save Energy Now initiative conducted energy audits at numerous steel plants, identifying tens of millions of dollars in potential energy savings [18]. Notably, many of the recommended measures had a payback period of under two years, prompting widespread implementation [18].

The ENERGY STAR for Industry program offers industry-specific best practice guides (including for steel) and recognizes top-performing plants. A strong emphasis is placed on modernizing energy equipment - replacing outdated boilers, compressors, and motors with high-efficiency models. According to a 2021 BlueGreen Alliance study, the overall energy intensity of the U.S. steel sector is about 33% lower than in China, despite the relatively high average age of U.S. BF–

BOF facilities (oxygen converters average over 30 years). This underscores the effectiveness of combining a high EAF share with targeted energy-efficiency policies.

China, the world’s largest steel producer (accounting for over 50% of global output), is also the largest energy consumer in the steel sector [25]. Between 2000 and the 2010s, China embarked on extensive modernization: thousands of small inefficient furnaces were closed and replaced with modern large-scale BF and BOF units. Over 80% of China’s BF–BOF capacity was built after 2000, many equipped with advanced technologies (gas recovery, pulverized coal injection, automation) [18]. As a result, specific energy consumption at major Chinese plants now approaches levels in developed countries. International benchmarking shows that China ranks second among 15 countries in energy efficiency for the BOF route [18].

However, China’s national average is lower due to a historically low EAF share (<10%). The Chinese government is addressing this by setting targets to raise the EAF share. The 2024–2025 Action Plan aims to increase the EAF share to 15% of total production and raise scrap use to 300 million tonnes/year [26]. By 2025, at least 30% of Chinese steel capacity must reach benchmark energy efficiency levels; underperforming plants are to be upgraded or phased out [26]. All new and retrofitted projects must meet A-level efficiency and environmental standards. China also provides financial incentives: green technology loans, subsidies for heat recovery systems, and strict energy consumption caps. While progress continues, China faces the challenge of rising domestic steel demand, which outpaces the deployment of energy-efficient technologies [6].

India, the world’s second-largest producer, also struggles with high energy intensity (among the highest globally, alongside China and Ukraine) [25], due to reliance on BF and coal-based DRI. The PAT program (Perform, Achieve and Trade) introduces specific energy reduction targets and allows certificate trading, incentivizing modernization or purchase of energy savings from more efficient firms.

Ukraine, historically among the top 10 producers, had an outdated production structure prior to the war (predominantly open-hearth and Bessemer converters until the 2010s, then BF–BOF), resulting in very high energy intensity. International assessments ranked Ukraine among the least energy-efficient producers globally, along with China and India [25]. However, post-war reconstruction is seen as an

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opportunity to implement state-of-the-art technologies. National recovery plans include building new EAF capacity, a green hydrogen metallurgy cluster, and other advanced infrastructure - aiming to bring Ukrainian steel to global energy performance levels [27].

At the global level, international organizations play a vital role. UNIDO has implemented multiple energy efficiency projects in steel across developing countries - from Egypt to Vietnam - offering expert support, benchmarking, and funding for BAT deployment [28]. The OECD explores energy policy mechanisms (e.g., 2019 reports on resource efficiency and steel decarbonization). The IEA's 2020 Steel Roadmap emphasized energy efficiency as a foundation for achieving carbon neutrality in the sector [29].

In summary, global experience confirms that countries investing early in energy-efficient technologies (Japan, EU, South Korea, USA) now enjoy competitive advantages and reduced energy price exposure, while those that delayed modernization must now leap toward advanced solutions - often with support from international initiatives.

4. Economic Aspects and Payback of Energy Efficiency Measures. Energy efficiency in the steel industry is closely tied to production economics. Energy carriers constitute a significant share of operating costs at metallurgical enterprises - on average, 20–40% of steel production costs [11]. Therefore, any improvement in efficiency directly reduces costs and enhances product competitiveness. According to IEA estimates, the implementation of readily available energy-saving technologies could save the industry hundreds of millions of dollars through reduced specific fuel consumption [11].

However, the adoption of new technologies requires capital investment, and decisions are often contingent upon the expected payback period. Most "low-hanging fruit" in energy efficiency - such as process optimization, insulation, heat recovery, and auxiliary equipment upgrades - offer relatively short payback periods. As previously mentioned, nearly two-fifths of energy-saving projects in the U.S. steel industry demonstrated a payback of less than one year, and the vast majority paid off within two years [18]. This indicates that such investments typically generate rapid economic returns.

On the other hand, large-scale capital-intensive projects - such as building a new EAF to replace a blast furnace, implementing a hydrogen facility, or comprehensive modernization of a BOF shop - may require hundreds of millions of dollars and have payback periods spanning decades. Companies are often reluctant to undertake these investments without additional incentives, as market-driven benefits alone may not justify the long investment cycles and associated risks (e.g., volatility in steel and energy prices).

Thus, government support programs play a critical role. Many countries have introduced mechanisms such as tax incentives for energy-efficient equipment, preferential loans, decarbonization funds, or direct subsidies. In the EU, for example, the Energy Efficiency Directive (EED) and related regulations explicitly recommend prioritizing support for high-efficiency cogeneration in industrial facilities [24].

In the United States, recent legislation (notably the Inflation Reduction Act of 2022) provides credits for industrial emission reduction, which also cover energy efficiency improvements. Payback times vary depending on the technology: for instance, installing variable frequency drives on motors can recover investment in 1–1.5 years through electricity savings, while coke dry quenching systems are more expensive and may take 5–7 years to pay back, depending on electricity and coal prices. Government grants and tax breaks reduce the effective payback period, making such projects more attractive.

Beyond direct economic benefits such as lower energy bills, improved energy efficiency also yields indirect advantages. These include enhanced energy security (reduced dependence on external fuel sources), lower environmental compliance costs (as CO_2 and pollutant emissions become increasingly taxed), and job creation in the manufacturing and servicing of green technologies [38]. According to the IEA, investments in industrial energy efficiency create approximately 18 jobs per $1 million invested, thanks to the development of supporting technologies and services [11].

Thus, the economic dimension of energy efficiency is multifaceted: on one hand, it enables cost reduction and fast returns for many measures; on the other, it requires significant capital for deep modernization. Therefore, comprehensive policy

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frameworks and financial incentives are essential to facilitate and accelerate this transition in the steel industry.

Conclusions

The steel industry remains one of the most energy-intensive sectors globally, yet it also holds some of the greatest potential for energy savings. In recent years, a substantial body of international experience has been accumulated in improving energy efficiency - ranging from equipment modernization to the implementation of digital control systems. Key indicators, such as specific energy consumption per tonne of steel, demonstrate positive trends, although the pace of improvement varies across regions.

The most successful countries have managed to combine technological innovations (such as heat recovery, electric arc furnaces, and automation) with well-designed public policy frameworks. This has enabled them to reduce the energy intensity of steel production to levels approaching theoretical minimums. On the other hand, a large share of global steelmaking still operates far from Best Available Techniques (BAT), leaving considerable untapped potential for energy savings.

A review of literature and industrial reports indicates that implementing currently available technologies - such as cogeneration, heat recovery, and process optimization - can reduce fuel consumption by 10–20% even at modern facilities [11]. Furthermore, transitioning to advanced production processes (e.g., scrap-based electric steelmaking, direct reduction) can deliver savings of 60–70% compared to outdated routes [11].

Energy efficiency is strongly linked to competitiveness: lower energy use results in reduced production costs and greater resilience to market volatility. Equally important is the role of energy efficiency in decarbonizing the steel industry. According to various estimates, energy-saving and material-efficiency measures (such as increased scrap recycling and reduced process losses) alone could lower the sector’s emissions by 15–20% by 2030 [11], contributing significantly to carbon neutrality goals.

International cooperation - including the exchange of best practices, joint research initiatives, and global benchmarking - plays a crucial role in accelerating progress.

In conclusion, the experience of different countries demonstrates that investments in energy efficiency within the steel industry are justified not only in terms of direct economic returns, but also through long-term environmental and energy security benefits. For Ukraine and other countries with energy-intensive steelmaking, the adoption of modern energy-efficient technologies is both an urgent necessity and a unique opportunity for technological leapfrogging - laying the groundwork for the sustainable development of the sector in the years to come.

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ПОНЯТТЯ ЕНЕРГОЕФЕКТИВНОСТІ В МЕТАЛУРГІЙНІЙ ПРОМИСЛОВОСТІ ТА ПОКАЗНИКИ ЇЇ ОЦІНКИ

Абстракт. *Метою роботи є аналітичне узагальнення теоретичних засад і практичних підходів до підвищення ефективності енергоспоживання в металургійній промисловості з урахуванням сучасних викликів кліматичної політики, зростання цін на енергоресурси, потреби в декарбонізації та економічної доцільності модернізації виробничих процесів.*

Методика. Дослідження базується на міждисциплінарному аналізі наукових публікацій, міжнародних звітів, статистичних даних, а також техніко-економічних характеристик виробництва сталі. Застосовано методи структурно-порівняльного аналізу енерговитрат за різними технологічними маршрутами, системний підхід до оцінки потенціалу інноваційних рішень та міжнародного бенчмаркінгу.

Результати. Визначено основні фактори енергоємності в металургії, обґрунтовано технологічні резерви підвищення ефективності – зокрема, перехід до електросталеплавильного виробництва, використання вторинної сировини, утилізацію втратного тепла, впровадження когенерації, цифровізації та водневої металургії. Розглянуто приклади успішної модернізації та програми стимулювання в провідних країнах.

Наукова новизна. У роботі систематизовано сучасні показники енергоефективності та маршрути виробництва сталі, охарактеризовано вплив різних технологічних стратегій на інтегральну енергоємність, а також запропоновано критерії оцінки потенціалу енергозбереження на макро- і мікрорівнях.

Практичне значення. Результати можуть бути використані для обґрунтування енергетичних стратегій підприємств, формування політик у сфері промислової декарбонізації, підготовки інвестиційних проєктів, а також розвитку державних і міжнародних програм підвищення енергоефективності в металургії.

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

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