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*Donets Dmytro***DECARBONIZATION OF THE METALLURGICAL INDUSTRY AS A FACTOR OF  
INCREASING INVESTMENT ATTRACTIVENESS: GREEN STEEL AND  
TECHNOLOGICAL TRAJECTORIES****Zaporizhzhia Polytechnic National University, Zaporizhzhia, Ukraine**

The article presents a comprehensive analysis of the decarbonization of the Ukrainian metallurgical industry as a strategic factor for increasing investment attractiveness in the context of European integration and the Carbon Border Adjustment Mechanism (CBAM). Three technological trajectories of green steel production are investigated: scrap-based electric arc furnaces (Scrap-EAF), hydrogen-based direct reduced iron with electric arc furnaces (H<sub>2</sub>-DRI-EAF), and hybrid solutions using natural gas (NG-DRI-EAF). A comparative analysis of the economic efficiency of investments in low-carbon technologies is conducted, accounting for critical operational shocks: energy crisis (electricity costs up to €250/MWh), coking coal deficit, and war risk premium (300-500 basis points). It is established that EAF technology provides 91-97% reduction in CO<sub>2</sub> emissions with capital expenditure of \$140-200 million per 1 million tons of capacity, but critically depends on access to low-carbon electricity and high-quality scrap. Hybrid NG-DRI-EAF technology is identified as the optimal transitional solution, providing 35-45% emissions reduction with strategic flexibility for gradual hydrogen transition (blending 10-100%). H<sub>2</sub>-DRI technology requires reduction of green hydrogen cost below \$2/kg for commercial viability at current prices of \$4-10/kg. It is proven that the CBAM mechanism creates critical pressure with potential losses of \$4.7 billion in 2026-2030, while opening opportunities to attract €36-59 billion in investments. The critical role of derisking mechanisms (Carbon Contracts for Difference, Ukraine Investment Framework) for reducing war risk premium and attracting international capital is substantiated. A three-phase strategy is defined with accelerated implementation of NG-DRI-EAF as backbone for ensuring high-quality primary feedstock and integration with nuclear energy for competitive green hydrogen production.

**Keywords:** green steel, metallurgical decarbonization, electric arc furnaces, hydrogen reduction, investment attractiveness, CBAM, technological trajectories, Ukrainian metallurgy.

**DOI:** 10.32434/2415-3974-2025-22-2-176-186***Introduction and problem statement***

The Ukrainian metallurgical industry stands at the crossroads of unprecedented global challenges and strategic transformation opportunities. The Russian invasion in February 2022 caused catastrophic losses in production capacity: the occupation of the Mariupol plants Azovstal and Ilyich Steel meant the disappearance of 30-40% of

the country's steelmaking capacity. Steel production collapsed from a historical peak of 21.37 million tons in 2021 to a critical 6.26 million tons in 2022 (a 71% decline), recovering only to 7.58 million tons in 2024 thanks to the opening of the maritime corridor [1]. Metinvest, the largest producer, lost approximately 65% of its business due to plant occupation.

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Parallel to direct military losses, the industry faced critical structural infrastructure shocks. The destruction by Russian attacks of over 70% of Ukraine's energy system generating capacity led to the necessity of massive electricity imports at market prices of € 150-250/MWh during peak periods, which is 3-5 times higher than prices in competitive European jurisdictions [3]. The closure of the Pokrovsk Coking Plant in January 2025, which provided 66% of the domestic coking coal market, means the necessity of importing 2.5 million tons of coking coal annually with additional costs of \$50-80/t of steel [1]. The mobilization of 15-20% of metallurgical industry workers creates a paradoxical shortage of skilled personnel against the backdrop of high overall unemployment.

Parallel to wartime challenges, the industry faces fundamental transformation of global markets. The EU's Carbon Border Adjustment Mechanism (CBAM), which entered into force in the transitional period from October 2023, creates a new economic imperative for decarbonization. Ukrainian metal is traditionally produced with emissions of 2.3 tons of CO<sub>2</sub>, per ton of steel, which radically exceeds European indicators (0.4-0.8 t CO<sub>2</sub>, /t for EAF) and is twice higher than global indicators for electric arc furnaces [3]. According to expert estimates, Ukrainian metallurgy may suffer export losses of up to \$4.7 billion in the 2026-2030 period due to high carbon intensity of production [2].

This creates not only environmental but also critical economic challenges for exports to the EU, which historically accounted for over half of all Ukrainian merchandise exports. However, paradoxically, these very challenges open a unique window of opportunity for fundamental transformation of the industry into a strategic competitive advantage through the implementation of green steel technologies and attraction of large-scale international investments.

The relevance of the research is determined by the critical need to identify optimal decarbonization technological trajectories that would simultaneously ensure economic efficiency, technological feasibility under conditions of structural operational shocks, investment attractiveness accounting for war risk premium, and compliance with European environmental standards in post-war reconstruction. The global green steel market demonstrates exponential growth: according to Future Business Insights forecasts, the global green steel market will reach \$89 billion by 2032 with an annual growth rate of 20.9% [4], creating strategic opportunities for Ukraine as a potential supplier of low-carbon steel and direct reduced iron (DRI) to the European market. Meanwhile, the global industry has already announced green steel projects totaling over €100 billion, with the highest

concentration in Europe [15].

#### *Analysis and review of publications*

The problem of metallurgical industry decarbonization is actively studied in world scientific literature. Fundamental research by Omodara et al. (2023) [5] in the journal *Nature Communications* (Q1, IF=16.6) presents a geospatial analysis of over 300 locations to determine optimal placement of green steel production based on H<sub>2</sub>-DRI-EAF technology. The authors established that competitive production is characterized by a combination of high-quality renewable energy sources (primarily solar complemented by wind) and DR-grade iron ore deposits. Critically, the study shows that Ukraine can gain the greatest advantage in relative competitiveness from the transition to green metallurgy due to a combination of factors.

A systematic approach to decarbonizing the global steel industry is presented in the work of Watari and McLellan (2024) [6], published in *Philosophical Transactions of the Royal Society A* (Q1). The researchers applied the methodology of “supply forecasting and demand backcasting,” proving that global steel production will not be able to grow within the Paris carbon budget, forecasting a deficit of about 30% against 2050 demand. This emphasizes the critical importance of efficient use of three limited resources: geological carbon storage (CCUS), zero-emission electricity, and secondary scrap metal. The findings of the study contrast with the conventional approach that emphasizes investment in new technologies, instead highlighting the need to reduce demand, upcycle scrap, and ensure a fair allocation of limited production.

Technological challenges of hydrogen metallurgy are analyzed in detail by Basirat (2024) [7] in an IEEFA analytical report. The author critically assesses the prospects of H<sub>2</sub>-DRI-EAF technology after 2024, warning against excessive optimism in green hydrogen production forecasts. According to BloombergNEF data, 64% of primary steel production by 2050 will be associated with H<sub>2</sub>-DRI-EAF technology, while Basirat emphasizes the need for realistic assessment: green hydrogen production will be more limited and expensive than often forecasted. Critically, the IEA warns that achieving LCOH <\$2/kg by 2030 is expected only for Chinese projects, casting doubt on the feasibility of rapid transition to 100% hydrogen without massive subsidies.

Political-economic analysis of decarbonization is presented by Karlsson et al. (2024) [8] in the journal *Climate Policy* (Q1), who study strategies of phase-in and phase-out in leading steel-producing jurisdictions. Key conclusion: existing policies focus

exclusively on green steel phase-in without simultaneous planned phase-out of high-carbon capacities. This creates systemic risk of overcapacity, trade conflicts, and slowing global transformation. The authors argue that phase-out policies play a critical role in overcoming inertia and exit barriers, thereby accelerating the decommissioning of obsolete capacities.

Financial aspects of low-carbon transformation are studied by Wang et al. (2025) [9] in the journal *Carbon Footprints for the Chinese steel industry*. The authors estimate a financial gap of 3.5 trillion yuan (\$490 billion) to achieve peak emissions and an additional 19 trillion yuan (\$2.7 trillion) for carbon neutrality. It is emphasized that low-carbon technologies (Scrap-EAF, DRI-EAF, CCUS) are characterized by high capital expenditures and increased investment risks due to policy uncertainty. A critical role is assigned to state-led investment guidance, green financial policies (such as green credit, carbon pricing, and R&D subsidies), and innovations in carbon finance instruments.

The study by Vogl et al. (2021) [12] in the journal *Energy Conversion and Management* (Q1, IF=10.4) presents a detailed techno-economic analysis of the entire green steel production chain using renewable energy sources. The authors established levelized cost of steel (LCOS) for different technological configurations, showing that H<sub>2</sub>-DRI-EAF can achieve competitiveness with traditional BF-BOF at carbon prices of €80-120/t CO<sub>2</sub> and electricity costs below €40/MWh.

Despite a significant volume of high-quality international research, there is a substantial scientific gap in defining specific decarbonization trajectories for Ukrainian metallurgy. Ukraine's unique resource capabilities and specific constraints (energy crisis with electricity costs up to ^250/MWh, coking coal shortage, labor shortage, war risk premium of 300-500 basis points) create the need to adapt global technological solutions to the national context accounting for critical operational shocks. This underscores the scientific novelty and practical significance of a comprehensive study on the economic efficiency of various technological pathways for Ukraine's metallurgy under structural challenges.

#### **Article objective**

The objective of this article is to determine optimal technological trajectories for decarbonization of the Ukrainian metallurgical industry through comprehensive comparative analysis of the economic efficiency of EAF, DRI-H<sub>2</sub>, and hybrid NG-DRI technologies accounting for critical operational shocks (energy crisis, coking coal deficit, war risk premium), assessment of their impact on industry investment

attractiveness, substantiation of financial derisking mechanisms, and development of a phased transformation strategy with emphasis on the strategic role of NG-DRI-EAF as a transitional backbone for ensuring high-quality primary feedstock and integration with nuclear energy for competitive green hydrogen production in the context of post-war reconstruction and European integration.

#### **Main Material**

Technological decarbonization trajectories: comparative analysis. Global practice of metallurgical decarbonization demonstrates clear differentiation of three main technological pathways, each characterized by specific technical parameters, economic efficiency, and Technology Readiness Level (TRL). Scrap-based electric arc furnaces (Scrap-EAF), hydrogen-based direct reduced iron with electric arc furnaces (H<sub>2</sub>-DRI-EAF), and hybrid solutions using natural gas (NG-DRI-EAF) represent a sequence of technological maturity from full commercialization to pilot implementation.

Electric arc furnace technology (EAF) represents the most mature and rapidly implemented decarbonization pathway with Technology Readiness Level TRL 9 (full commercial availability). Capital expenditures for building an EAF plant with 1 million tons per year capacity amount to \$140-200 million, which is 5-7 times lower than traditional blast furnace-basic oxygen furnace (BF-BOF) complexes, which require \$900 million-1.2 billion investments [10]. This dramatic difference in capital costs makes EAF the most accessible entry point for decarbonization under conditions of limited capital access.

The technology provides 91-97% reduction in CO<sub>2</sub> emissions compared to the BF-BOF route, achieving extremely low indicators of 0.05-0.2 tons of CO<sub>2</sub> per ton of steel when using renewable electricity [3]. For comparison, the conventional BF-BOF route generates 1.8-2.3 tons of CO<sub>2</sub> per ton of steel. Real-world projects confirm these figures: POSCO's plant in South Korea, with an investment of \$452 million, demonstrates that EAF technology can be rapidly deployed with predictable economic performance [11].

The economic efficiency of EAF is determined by several critical factors, which are particularly acute in Ukrainian conditions. First, operating costs critically depend on electricity cost, which constitutes 40-50% of operating expenses. Under the current energy crisis – triggered by the destruction of 70% of generating capacity – imported electricity may cost €150-250/MWh during peak periods [1,3]. This structural price disparity creates a significant OPEX disadvantage compared to EU competitors, where electricity prices range from €50 to €80/MWh. As a result, the economic benefits of

lower CAPEX and savings on carbon payments may be entirely offset. Under baseline European conditions, the production cost of one ton of steel via the EAF route amounts to €450–550, compared to €600–700 for the BF–BOF process [2]. However, for Ukraine, these figures deteriorate drastically due to the energy factor. Second, availability of high-quality scrap metal is systemically limited. Scrap metal is generated 30–50 years after its initial production; therefore, its supply lags behind the growing demand. For Ukraine, the problem is exacerbated by high scrap cost (\$534/t compared to \$212/t in China) [5], creating the need for alternative sources of metallized feedstock. Mass expansion of EAF capacities, as planned by Zaporizhstal (3.3–3.8 million t/year) and Kametstal (3.2 million t/year), will inevitably create acute scrap shortage, justifying the critical need to develop DRI infrastructure.

At current EU carbon quota prices (€30–90/t CO<sub>2</sub> in 2024), savings on carbon payments amount to €140–180 per ton of steel, significantly improving competitiveness. Payback period for investments is estimated at 5–7 years at carbon prices above €50 per ton of CO<sub>2</sub>. According to McKinsey estimates, internal rate of return (IRR) for EAF projects is 12–18% at carbon price of €0/t [15].

However, EAF technology faces systemic product quality limitations: scrap-based steel is constrained by impurity accumulation from residual elements (such as copper and tin), rendering it unsuitable for certain high-grade applications (e.g., automotive-grade steel). Thus, the success of short-term EAF expansion directly depends on securing a stable supply of high-quality metallic feedstock – namely, direct reduced iron (DRI/HBI).

Hydrogen direct reduction (H<sub>2</sub>-DRI-EAF) represents revolutionary technology with potential for almost complete decarbonization (TRL 7–8, expected commercialization 2026–2035). The process uses hydrogen to reduce iron ore, producing direct reduced iron (DRI) with emissions of only 50–160 kg CO<sub>2</sub> per ton when using green hydrogen compared to 1,800–2,300 kg for traditional methods [7]. The DRI is then melted in an EAF to produce steel, forming an integrated low-carbon production route.

Capital expenditures are significantly higher: €900–1,650 per ton of steel capacity, including DRI installation, EAF, and electrolyzers for hydrogen production [11]. The total capital expenditure for a metallurgical plant with an annual production capacity of 2.5 million tons (corresponding to the modular size planned by Metinvest) is estimated to potentially range from €2.5 billion to €4.0 billion. For comparative analysis, H<sub>2</sub> Green Steel in Sweden secured a record

€6.5 billion in funding for a 5.0 million-ton facility.

The financial structure of this capital raise comprises: €1.8 billion in equity, €4.2 billion in debt financing, and €0.5 billion sourced from government subsidies [4].

A critical factor of economic viability is the cost of green hydrogen (Levelized Cost of Hydrogen, LCOH). According to current 2024 estimates, green hydrogen production through electrolysis costs \$4–10/kg. For competitiveness with traditional methods, a price below \$2/kg is required [4], requiring reduction of electricity cost to €20–30/MWh. According to IEA forecasts, such price can be achieved in 2030–2035 only in regions with best conditions, predominantly in China [7].

Given this, Ukraine’s H<sub>2</sub>-DRI-EAF strategy must be integrated with expansion of nuclear energy capacity. Nuclear power plants provide stable, low-carbon baseload electricity generation with intensity of 12 g CO<sub>2</sub>/kWh and target price of €40–50/MWh [1]. This is the only way to ensure high electrolyzer capacity factor (>70%), which is a necessary condition for achieving competitive LCOH <\$2/kg. Integration with nuclear energy is crucial, as renewable energy sources in Ukraine are constrained by military operations and characterized by a low capacity utilization factor (20–35% for wind, 15–20% for solar).

The infrastructural requirements are substantial: a facility producing 1 million tons of steel annually necessitates 600 MW of electrolysis capacity to yield 55,000–60,000 tons of hydrogen per annum, consuming 3.0–3.6 TWh of electricity. This consumption is equivalent to the output of a 750–1,000 MW solar or wind power plant operating with a capacity utilization factor of 35–40% [7]. Capital expenditure for electrolyzers currently amounts to €250–300 per ton of steel capacity in 2024, with projections indicating a decline to €120–180/t by 2030, driven by economies of scale and technological advancements.

Hybrid natural gas solutions (NG-DRI-EAF) represent the optimal transitional strategy with TRL 8–9 and wide commercial availability. Using natural gas for direct reduction reduces emissions to 1.1–1.3 tons of CO<sub>2</sub> per ton of steel, providing 35–45% improvement compared to BF–BOF [7]. This technology has critical strategic advantage of flexibility: DRI installations can operate on pure natural gas with gradual hydrogen blending (10%, 30%, 50%) until achieving full transition to 100% hydrogen [1,8].

The main advantage of NG-DRI-EAF lies not only in emissions reduction but also in solving the critical bottleneck – ensuring high-quality primary

metallized feedstock for mass expansion of EAF capacity. Corporate plans, such as Metinvest’s intention to build two DRI modules with capacity of 2.5 million tons per year each using local DR-grade ore, confirm this approach as the main path to ensuring feedstock sustainability [2]. Chinese company Baowu demonstrates successful implementation of the hybrid approach: utilization of coke oven gas as a hydrogen source enabled achievement of 500,000 tons CO<sub>2</sub> reduction per year at the Zhanjiang plant with minimal

additional investments [3].

Capital expenditures for NG-DRI-EAF are intermediate between EAF and the fully hydrogen route: €450-700 per ton of capacity, making the technology financially realistic for the medium-term horizon (Table 1). Critically, NG-DRI ensures immediate emissions reduction while preserving the possibility of gradual hydrogen transition as green H<sub>2</sub>, achieves economic viability, avoiding the risk of stranded assets.

Table 1

Comparative Characteristics of Decarbonization Technologies

| Parameter                            | BF-BOF (traditional) | Scrap-EAF          | NG-DRI-EAF (hybrid) | H <sub>2</sub> -DRI-EAF |
|--------------------------------------|----------------------|--------------------|---------------------|-------------------------|
| CO <sub>2</sub> emissions, t/t steel | 1.8-2.3              | 0.05-0.2           | 1.1-1.3             | 0.05-0.16               |
| CAPEX, \$ million / 1 million t      | 900-1,200            | 140-200            | 450-700             | 900-1,650               |
| Payback period, years                | 15-25                | 5-7                | 7-10                | 8-12                    |
| TRL                                  | 9                    | 9                  | 8-9                 | 7-8                     |
| Critical driver                      | Coke, Carbon         | Electricity, Scrap | Gas Price           | Hydrogen Price          |

Source: compiled by author based on [5, 7, 10, 12]

Analysis of structural risks and operational shocks. Critical analysis reveals structural operational risks that may slow or derail implementation of decarbonization strategy if not addressed at state policy and investment planning level (Table 2).

Energy crisis as defining OPEX risk. Destruction of over 70% of energy infrastructure, resulting in loss of about 9 GW of generating capacity [3], is the biggest short-term risk for decarbonization. The necessity of electricity imports at prices 3-5 times higher than in competitive EU jurisdictions (€150-250/MWh vs €50-80/MWh) creates structural cost disadvantage for energy-intensive EAF and future DRI complexes.

Success of green metallurgy, which will require 20-25 TWh of additional low-carbon electricity for full industry transformation [1], depends on priority restoration and expansion of stable nuclear generation, providing competitive prices (€40-50/MWh) and high capacity factor for electrolyzers and EAF. Without addressing the energy crisis, even projects characterized by low capital expenditures will have uncompetitive operational expenditures, making them unbankable for private investors.

Globally, the traditional BF-BOF route requires planned phase-out policies to prevent excess capacity [8, 12]. In Ukraine, the military threat to the sole operational coking coal mine near Pokrovsk, coupled with the closure of the Pokrovsk Coke Plant in January 2025—which supplied 66% of the domestic market—creates conditions for forced phase-out of most existing integrated metallurgical plants [1,13].

The loss of this infrastructure is expected to result in a 50-70% decline in total steel production for blast furnace-dependent enterprises [13] and increase production costs by \$50-80/t of steel due to the necessity of importing coking coal or coke [1]. This crisis does not merely present a challenge but effectively renders preservation of the traditional BF-BOF model impossible, thereby substantiating the imperative to concentrate all limited financial resources exclusively on DRI/EAF projects as the sole viable pathway for production recovery.

Against a backdrop of high unemployment (projected at 18.9% in 2023) [14], the metallurgical industry faces an acute shortage of qualified personnel, as 15-20% of workers have been mobilized into the armed forces [1]. This creates a paradoxical deficit of skillsets required for operating high-technology DRI-EAF complexes. Successful transformation necessitates immediate, large-scale investments in vocational education and training (VET) and workforce retraining to ensure an adequate supply of qualified labor.

Investment attractiveness of decarbonization: CBAM, derisking mechanisms, and capital structure. The investment attractiveness of green technologies in metallurgy is formed through a complex interaction of direct economic benefits, regulatory incentives, access to specialized green financial instruments, and derisking mechanisms under conditions of high war risk premium. The EU CBAM mechanism creates a powerful economic push-factor for decarbonization through direct monetization of carbon intensity.

Table 2

**Quantitative Assessment of Major Operational Risks**

| Risk factor         | Key impact                        | Quantitative assessment                                       | Criticality |
|---------------------|-----------------------------------|---------------------------------------------------------------|-------------|
| Energy crisis       | OPEX increase EAF/DRI             | €150-250/MWh (peak) vs €40-50/MWh                             | HIGH        |
| Coking coal deficit | BF-BOF cost increase              | Additional costs \$50-80/t, risk of 50-70% production decline | HIGH        |
| CBAM payments       | Loss of BF-BOF competitiveness    | Additional payment €160-184/t steel (23-31% of export price)  | CRITICAL    |
| War risk premium    | Increased cost of capital (WACC)  | 300-500 basis points premium to WACC                          | HIGH        |
| Labor shortage      | Mobilization of qualified workers | 15-20% of workforce                                           | HIGH        |

Source: compiled by author based on [1, 2, 3, 9, 10]

For Ukrainian metallurgy, CBAM represents an existential challenge: according to detailed calculations by Low Carbon Ukraine, the industry may experience export losses of \$4.7 billion during 2026-2030 and up to €248 million in annual EBITDA losses due to high carbon intensity of 2.3 t CO<sub>2</sub>/t steel [2]. With an average steel export price of €600-700/t and carbon price of €80/t, additional CBAM certificate costs amount to €160-184/t, equivalent to 23-31% of the export price – a catastrophic blow to the competitiveness of traditional BF-BOF production.

Simultaneously, CBAM creates a powerful pull-effect for green investments through a competitive advantage mechanism. Low-carbon steel producers receive a reverse subsidy effect: at emissions of 0.1 t CO<sub>2</sub>/t (EAF on renewable energy), savings on CBAM payments compared to competitors (2.0 t CO<sub>2</sub>/t) amount to €152/t, creating a structural competitive advantage and justifying premium pricing for green steel (+10-15% price premium).

Implementation of large-scale green steel projects with investment needs of €36-59 billion will face high war risk premium (300-500 basis points) [1, 2], which radically increases the cost of capital (WACC) from typical 8-10% to 12-15%, making projects unbankable for private investors without state support. Overcoming this financial barrier requires application of innovative derisking mechanisms.

Carbon Contracts for Difference (CCfD) play a critical role, guaranteeing investors a minimum carbon price (e.g., €80-100/t), protecting against EU ETS market volatility. The mechanism operates as a two-way contract: if the market carbon price falls below the strike price, the state compensates the producer for the difference; if the price is above the strike price, the producer returns the difference to the state. This reduces market risk and makes long-term

investments predictable. Germany has already implemented a €4 billion CCfD program to support green steel projects of ThyssenKrupp and Salzgitter [9].

The Ukraine Investment Framework (UIF), created as part of the €50 billion Ukraine Facility from the EU [11], can provide credit guarantees and first-loss capital to attract private debt financing. Guarantees from international financial institutions (World Bank, EBRD, EIB) reduce perceived risk for commercial banks, enabling structuring of competitive debt financing. Reference example: H2 Green Steel attracted €4.2 billion in debt financing thanks to €0.5 billion in state guarantees and €1.8 billion in equity from strategic investors (Scania, Mercedes-Benz) [4].

Global green steel projects demonstrate growing investor interest in well-structured green steel ventures. According to the Stockholm Environment Institute, projects totaling over €100 billion were announced in 2020-2024, concentrated in Europe (60%), Asia (25%), and the Middle East (10%) [15]. Metinvest plans €2.5 billion investment in a DRI-EAF plant in Italy (Porto Maghera) with capacity of 2.7 million tons, which will be the largest green steel project in Southern Europe [11]. ArcelorMittal received €1.3 billion from the German government, €850 million from France, €460 million from Spain for decarbonization of European operations [3], however, the consortium's total need is estimated at \$40 billion, demonstrating the scale of the financial gap and necessity of state support.

For Ukraine, the total investment need for complete metallurgical decarbonization is estimated at €36-59 billion under various scenarios [2] (Table 3). With proper structuring and state support, such investments can provide attractive returns: according to estimates, ROI is \$3.28 per \$1 invested through a combination of carbon payment savings (\$2 billion/year), premium pricing for

green steel (+10-15% price premium = \$0.8 billion/year), and new export opportunities (additional \$0.5 billion/year) [10]. The cumulative potential for additional value by 2050 is estimated at \$164 billion.

Table 3

**Decomposition of Ukraine’s Investment Requirements for Metallurgical Decarbonization (2025–2050)**

| Investment direction            | CAPEX (€ billion) | Purpose/impact                                                      |
|---------------------------------|-------------------|---------------------------------------------------------------------|
| EAF capacity                    | 10-15             | Rapid emissions reduction, scrap recycling, short payback period    |
| DRI-H <sub>2</sub> /NG capacity | 20-35             | Ensuring high-quality primary feedstock, hydrogen-ready flexibility |
| Electrolyzers                   | 6-9               | Green hydrogen production based on nuclear/renewables, LCOH <\$2/kg |
| Grid modernization and nuclear  | 3-5               | OPEX reduction, ensuring stable supply €40-50/MWh                   |
| Total investments               | 39-64             | Total need requiring international guarantees and CCfD              |

Source: compiled by author based on [1, 2, 11, 15]

Critical is access to green financial instruments. Green bonds have become a mainstream instrument: the European green bond market reached €500 billion outstanding in 2024 [9]. ArcelorMittal issued \$1 billion in green bonds in 2023 with a 3.5% coupon, 50 basis points below ordinary corporate debt due to green premium discount. However, Ukrainian companies face a 300-500 basis point war risk premium, which radically increases the cost of capital and requires creative financial structuring with guarantees from international financial institutions, use of CCfD

Specifics of Ukrainian metallurgy: resource advantages and strategic opportunities. Ukraine possesses a unique combination of competitive advantages for low-carbon metallurgy development that can transform decarbonization challenges into strategic opportunities. First, the country has large reserves of high-quality DR-grade (direct reduction) iron ore suitable for DRI technologies. Kryvbas contains over 20 billion tons of proven iron ore reserves with iron content of 55-65% after beneficiation, which is ideal for direct reduction processes [2]. This creates a unique opportunity for Ukraine to become a major supplier of DRI and HBI not only for the domestic market but also for the European market, which is experiencing a shortage of high-quality scrap.

Second, the presence of three operating nuclear power plants (Rivne, Khmelnytskyi, South Ukraine) with total installed capacity of approximately 13 GW and plans for nuclear capacity expansion create unique potential for stable, low-carbon baseload electricity generation. Nuclear generation has carbon intensity of only 12 g CO<sub>2</sub>/kWh compared to 400-900 g CO<sub>2</sub>/kWh for coal generation [2]. With a target nuclear electricity

price of €40-50/MWh, Ukraine can compete with the best renewable energy locations in the world and ensure high electrolyzer capacity factor (>70%), which is critical for achieving LCOH <\$2/kg.

Concrete transformation plans are already forming. Metinvest has announced its intention to build two DRI modules in Ukraine, each with capacity of 2.5 million tons per year, which will supply metallized feedstock to new EAF complexes at Zaporizhstal and Kamet Steel. Total investments are estimated at \$5-7 billion [11]. ArcelorMittal Kryvyi Rih is considering transition from BF-BOF to DRI-EAF route with potential investments of €3-4 billion. The total amount of announced green steel projects in Ukraine is \$11 billion, or \$1,450 per ton of current production [11], confirming the seriousness of industry intentions.

Priorities of technological transformation: accelerated implementation of NG-DRI as strategic backbone. Based on comprehensive analysis of technological options, economic efficiency accounting for operational shocks, resource capabilities, and derisking mechanisms, a three-phase decarbonization strategy for Ukrainian metallurgy can be defined with clear sequencing of investments, realistic milestones, and emphasis on accelerated implementation of NG-DRI-EAF as critical transitional backbone.

The short-term horizon (2025-2030) should focus on aggressive expansion of EAF capacities for processing available scrap and imported HBI with simultaneous resolution of the energy crisis. Priority actions: construction of 4-6 new EAF complexes with capacity of 1.5-2.0 million tons each (total investments €1.2-1.8 billion, IRR 15-18% with energy supply

resolution); modernization of existing EAF with 15-20% energy efficiency improvement; development of scrap collection and processing infrastructure; import of HBI from the Middle East as bridging solution until launch of own DRI capacities. Critical: simultaneous resolution of the energy crisis by ensuring competitive electricity prices for industry (target €50-80/MWh) through restoration and expansion of low-carbon nuclear baseload generation.

This will ensure rapid emissions reduction of 8-10 million tons CO<sub>2</sub>/year with relatively low capital costs and short implementation period (2-3 years), but will not solve the fundamental problem of high-quality metallized charge deficit.

The medium-term horizon (2030-2040) envisages a strategic shift to NG-DRI-EAF capacities not simply as one of the options, but as a priority backbone for ensuring necessary volumes of high-quality primary steel and resolving feedstock deficit for EAF. Priority actions: construction of 3-4 DRI modules with capacity of 2.5 million tons each on natural gas (total investments €6-9 billion, which should be prioritized in state strategy); development of gas pipeline infrastructure and storage; critical: incorporation of hydrogen-ready capability with possibility of blending 30-50% hydrogen in gas stream for gradual transition; integration with Ukrainian nuclear baseload electricity for EAF operations.

NG-DRI-EAF is not merely a “medium-term phase” but a critical enabling factor for success of the entire strategy. This technology: (1) provides high-quality primary feedstock (DRI/HBI) for EAF scaling, (2) reduces emissions by 35-45% (to 1.1-1.3 t CO<sub>2</sub>/t) while maintaining commercial viability, (3) creates hydrogen-ready infrastructure for gradual transition to 100% H<sub>2</sub>, without stranded assets risk, (4) compensates for forced phase-out of BF-BOF due to coking coal deficit. Metinvest’s plans for two modules of 2.5 million t/year each confirm this approach as realistic and critically necessary.

The long-term horizon (2040-2050) focuses on complete transition to H<sub>2</sub>-DRI-EAF upon achieving three critical conditions: (1) green hydrogen <\$2/kg through scaling of green hydrogen economy and electrolyzer CAPEX reduction, (2) carbon price >€150/t creates compelling economics for complete decarbonization, (3) development of nuclear + renewable energy infrastructure for 20-25 TWh of additional low-carbon electricity. Priority actions: gradual conversion of NG-DRI modules to 100% hydrogen (using hydrogen-ready capability); construction of 2.0-2.5 GW electrolyzer capacity integrated with nuclear baseload generation (capacity factor >70% to achieve LCOH <\$2/kg); development

of hydrogen pipeline and storage infrastructure.

This will achieve near-zero emissions <0.1 t CO<sub>2</sub>/t steel and create opportunity for Ukraine to become exporter not only of green steel but also green hydrogen and DRI/HBI intermediate products for the European market.

Critical enabling conditions for strategy implementation: (1) post-war reconstruction financing from European integration funds (Ukraine Facility €50 billion) and IFI support; (2) Carbon Contracts for Difference (CCfD) with the EU guarantee long-term carbon price floor of €80-100/t, reducing market risk for investors; (3) green premium mechanism enables premium pricing of +10-15% for certified low-carbon steel, improving economics; (4) state aid for energy price compensation reduces electricity cost disadvantage during transition period; (5) EU-Ukraine green steel partnership ensures preferential market access, technology transfer, and financial support through UIF mechanisms; (6) large-scale VET programs for retraining 15-20% of mobilized workers.

### **Conclusions**

The study confirms that decarbonization of the metallurgical industry is not only an environmental imperative but also the only survival strategy and a strategic catalyst for radically increasing the investment attractiveness of Ukrainian metallurgy in the context of European integration, global steel market transformation, and critical operational shocks of the post-war period.

Comprehensive comparative analysis of technological trajectories accounting for specific Ukrainian challenges establishes that the optimal strategy lies in sophisticated sequencing of three complementary technologies with critical emphasis on accelerated implementation of NG-DRI-EAF: (1) rapid deployment of EAF for utilizing available scrap achieving 91-97% emissions reduction at lowest capital costs (\$140-200 million/million tons), however with critical dependence on energy crisis resolution (target electricity €50-80/MWh instead of current €150-250/MWh); (2) priority build-up of NG-DRI-EAF capacities as backbone for ensuring high-quality primary feedstock and compensating forced phase-out of BF-BOF due to coking coal deficit, with 35-45% emissions reduction and hydrogen-ready flexibility for gradual blending to 100% H<sub>2</sub>; (3) long-term transformation to H<sub>2</sub>-DRI-EAF upon achieving economic viability through LCOH reduction below \$2/kg critical threshold.

Economic analysis accounting for operational shocks demonstrates a compelling investment case for green technologies when enabling conditions are met: at current carbon prices of €80-90/t CO<sub>2</sub> and

projected growth to €150-200/t by 2040, decarbonization creates structural competitive advantage through CBAM payment savings (\$2 billion/year), green premium pricing (+10-15% = \$0.8 billion/year), and new export opportunities (\$0.5 billion/year). Overall ROI of \$3.28 per \$1 invested confirms economic attractiveness subject to successful application of derisking mechanisms.

The CBAM mechanism creates a dual effect: threat of export losses of \$4.7 billion in 2026-2030 due to high carbon intensity of 2.3 t CO<sub>2</sub>/t creates urgent imperative; simultaneously, successful decarbonization opens access to €36-59 billion in green investments and potential additional value of \$164 billion by 2050, transforming CBAM from threat to strategic opportunity.

The greatest risk for investors is not technological uncertainty but high operational cost due to energy crisis (prices €150-250/MWh) and war risk premium (300-500 b.p.). Success critically depends on: (1) restoration and expansion of nuclear generation for baseload electricity at €40-50/MWh; (2) implementation of Carbon Contracts for Difference to guarantee carbon price floor of €80-100/t; (3) utilization of Ukraine Investment Framework for credit guarantees and attracting international private capital; (4) state support for compensating energy cost disadvantage during transition period.

The study substantiates that NG-DRI-EAF is not merely a medium-term phase but a critical enabling factor for the entire strategy because: (1) it resolves the deficit of high-quality metallized feedstock for EAF scaling; (2) compensates for forced phase-out of BF-BOF due to coking coal feedstock base collapse; (3) ensures hydrogen-ready flexibility for gradual transition without stranded assets; (4) achieves immediate 35-45% emissions reduction while maintaining commercial viability.

Ukraine's unique competitive advantages – massive reserves of DR-grade iron ore (20+ billion tons), existing nuclear energy capacity with expansion potential for stable baseload at 12 g CO<sub>2</sub>/kWh, and geographic proximity to the European market – create realistic potential to become a major supplier not only of green steel but also DRI/HBI intermediate products for European metallurgy.

Scientific novelty of the study lies in: (1) development of comprehensive three-phase strategy emphasizing accelerated NG-DRI implementation as critical backbone, adapted to post-war realities; (2) quantitative assessment of investment attractiveness integrating critical operational shocks (energy crisis, coke deficit, war risk premium); (3) substantiation of critical role of derisking mechanisms (CCfD, UIF)

for overcoming financial barriers; (4) demonstration of unique competitive advantages of DR-grade ore and nuclear baseload integration for competitive green hydrogen.

Practical significance of results lies in defining actionable priorities for: (1) state policy through targeted subsidies, CCfD implementation, UIF utilization, and energy price support; (2) corporate investment strategies with realistic timelines and NG-DRI backbone prioritization; (3) international financial institutions regarding structuring green finance instruments for high-risk post-conflict markets; (4) EU-Ukraine partnership in green steel development with preferential market access and technology transfer.

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## ДЕКАРБОНІЗАЦІЯ МЕТАЛУРГІЙНОЇ ГАЛУЗІ ЯК ФАКТОР ПІДВИЩЕННЯ ІНВЕСТИЦІЙНОЇ ПРИВАБЛИВОСТІ: GREEN STEEL ТА ТЕХНОЛОГІЧНІ ТРАЕКТОРІЇ

Донець Дмитро

Стаття присвячена комплексному аналізу декарбонізації української металургійної галузі як стратегічного фактора підвищення інвестиційної привабливості в контексті європейської інтеграції та механізму прикордонного вуглецевого коригування СВМ. Досліджено три технологічні траєкторії виробництва зеленої сталі: електродугові печі на основі брукхту (Scrap-EAF), водневе пряме відновлення з електродуговими печами (H<sub>2</sub>-DRI-EAF) та гібридні рішення з використанням природного газу (NG-DRI-EAF). Проведено порівняльний аналіз економічної ефективності інвестицій у низьковуглецеві технології з урахуванням критичних операційних шоків: енергетичної кризи (вартість електроенергії до €250/MWh), дефіциту коксівного вугілля та премії за воєнний ризик (300-500 базисних пунктів). Встановлено, що EAF-технологія забезпечує зниження викидів CO<sub>2</sub> на 91-97% при капітальних витратах \$140-200 млн на 1 млн. тон потужності, проте критично залежить від доступності низьковуглецевої електроенергії та високоякісного брукхту. Гібридна NG-DRI-EAF технологія визначена як оптимальне перехідне рішення, що забезпечує 35-45% зниження викидів при стратегічній гнучкості поступового переходу на водень. H<sub>2</sub>-DRI технологія потребує зниження вартості зеленого водню нижче \$2/кг для комерційної життєздатності при поточній ціні \$4-10/кг. Доведено, що механізм СВМ створює критичний тиск з потенційними втратами \$4,7 млрд у 2026-2030 рр., водночас відкриваючи можливості залучення €36-59 млрд інвестицій. Обґрунтовано критичне значення механізмів деризикації (Carbon Contracts for Difference, Ukraine Investment Framework) для зниження премії за воєнний ризик і залучення міжнародного капіталу. Визначено триетапну стратегію з прискореним впровадженням NG-DRI-EAF як базової перехідної технології для забезпечення високоякісною первинною сировиною та інтеграцією з ядерною енергетикою для конкурентоспроможного виробництва зеленого водню.

**Ключові слова:** зелена сталь, декарбонізація металургії, електродугові печі, водневе відновлення, інвестиційна привабливість, СВМ, технологічні траєкторії, українська металургія.

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## DECARBONIZATION OF THE METALLURGICAL INDUSTRY AS A FACTOR OF INCREASING INVESTMENT ATTRACTIVENESS: GREEN STEEL AND TECHNOLOGICAL TRAJECTORIES

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*The article presents a comprehensive analysis of the decarbonization of the Ukrainian metallurgical industry as a strategic factor for increasing investment attractiveness in the context of European integration and the Carbon Border Adjustment Mechanism (CBAM). Three technological trajectories of green steel production are investigated: scrap-based electric arc furnaces (Scrap-EAF), hydrogen-based direct reduced iron with electric arc furnaces (H<sub>2</sub>-DRI-EAF), and hybrid solutions using natural gas (NG-DRI-EAF). A comparative analysis of the economic efficiency of investments in low-carbon technologies is conducted, accounting for critical operational shocks: energy crisis (electricity costs up to €250/MWh), coking coal deficit, and war risk premium (300-500 basis points). It is established that EAF technology provides 91-97% reduction in CO<sub>2</sub> emissions with capital expenditure of \$140-200 million per 1 million tons of capacity, but critically depends on access to low-carbon electricity and high-quality scrap. Hybrid NG-DRI-EAF technology is identified as the optimal transitional solution, providing 35-45% emissions reduction with strategic flexibility for gradual hydrogen transition (blending 10-100%). H<sub>2</sub>-DRI technology requires reduction of green hydrogen cost below \$2/kg for commercial viability at current prices of \$4-10/kg. It is proven that the CBAM mechanism creates critical pressure with potential losses of \$4.7 billion in 2026-2030, while opening opportunities to attract €36-59 billion in investments. The critical role of derisking mechanisms (Carbon Contracts for Difference, Ukraine Investment Framework) for reducing war risk premium and attracting international capital is substantiated. A three-phase strategy is defined with accelerated implementation of NG-DRI-EAF as backbone for ensuring high-quality primary feedstock and integration with nuclear energy for competitive green hydrogen production.*

**Keywords:** green steel, metallurgical decarbonization, electric arc furnaces, hydrogen reduction, investment attractiveness, CBAM, technological trajectories, Ukrainian metallurgy.

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