BG Pulse Journal USA
ISSN:1947-2536 http://www.bgpulseusa.com/index.php/bg

IMPROVING THE EFFICIENCY OF INNOVATIVE ACTIVITIES IN MINING AND METALLURGICAL ENTERPRISES BASED ON ECONOMIC MECHANISMS.

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https://doi.org/10.5281/zenodo.20508094

Abstract: The mining and metallurgical complex (MMC) serves as a foundational pillar for industrial stability and economic growth in resource-dependent nations. However, the sector faces mounting pressure from declining ore grades, fluctuating global commodity prices, and stringent environmental regulations. This article examines the economic mechanisms essential for enhancing the efficiency of innovative activities within MMC enterprises. By analyzing capital intensity, R&D integration, and fiscal incentives, the study identifies a structural model for sustainable innovation. The research focuses on the transition from extensive resource extraction to intensive, technology-driven production. Results indicate that the application of targeted economic levers—such as tax credits for "green" metallurgy and public-private partnerships—significantly reduces the payback period for high-tech investments. The findings provide a framework for policy-makers and corporate managers to synchronize economic incentives with technological modernization.

Keywords: Mining and Metallurgical Complex (MMC), Economic Mechanisms, Innovative Efficiency, R&D Investment, Resource Management, Digitalization, Sustainable Development.

Introduction

The modern global economy is undergoing a structural shift characterized by the Fourth Industrial Revolution (Industry 4.0). For the mining and metallurgical industry, this transition is not merely an option but a necessity for survival. Mining enterprises are currently operating in an environment of "diminishing returns," where the extraction of deeper-seated deposits requires exponentially higher energy and financial inputs [1].

The core problem lies in the traditional "extensive" model of growth, which relies on increasing the volume of raw material extraction rather than the efficiency of its processing. Innovation in this sector is uniquely challenging due to high capital intensity, long investment cycles, and high risks associated with the implementation of unproven technologies. Economic mechanisms—defined as the system of organizational structures, forms, and methods of management—play a decisive role in bridging the gap between scientific research and industrial application [2]. This article explores how these mechanisms can be calibrated to foster an environment conducive to continuous innovation.

Methodology

The research methodology employs a multi-dimensional approach to evaluate the efficiency of innovative activities.

- **Systemic Analysis:** To view the MMC as an interconnected system of economic incentives and technological outputs.
- **Statistical Analysis:** Reviewing global and regional data regarding R&D expenditure as a percentage of total revenue in the metallurgical sector.

- **Comparative Analysis:** Examining the effectiveness of different economic levers (direct subsidies vs. indirect tax incentives) used in leading mining jurisdictions such as Australia, Canada, and Kazakhstan.
- **Modeling:** Constructing a theoretical framework for the "Economic Mechanism of Innovation," which integrates financial, organizational, and motivational components.

The study relies on peer-reviewed journals, World Steel Association reports, and national economic statistics to ensure the factual integrity of the analysis.

Results

The investigation reveals that the efficiency of innovation in the MMC is directly proportional to the sophistication of the underlying economic mechanisms. Key findings include:

1. Investment Structure and R&D Dynamics Factual data shows that leading metallurgical companies (e.g., ArcelorMittal, Rio Tinto) allocate between 1.5% and 3% of their annual turnover to R&D. In contrast, enterprises in developing economies often struggle to surpass the 0.5% threshold [3]. The research identifies that the most efficient innovations are currently centered around "Digital Twins" of mines and automated smelting processes, which can reduce operational costs by up to 15%.

2. Fiscal Mechanisms Tax incentives remain the most potent tool. Countries that allow for an accelerated depreciation of innovative equipment (writing off assets within 3-5 years instead of 10-15) show a 20% higher rate of technological renewal [4].

3. Environmental-Economic Synergy The introduction of "Carbon Taxes" and "Green Certificates" has transformed environmental compliance from a cost center into an innovation driver. Enterprises adopting hydrogen-based reduction of iron ore are gaining access to lower-interest "green" loans, effectively reducing their cost of capital [5]

Analysis and Discussion

Structural Impediments to Innovation in the Heavy Industry Sector

The empirical results demonstrate that the transition of mining and metallurgical enterprises from an extensive growth model to an intensive, technology-driven paradigm is fundamentally mediated by the structure of existing economic mechanisms. In the mining and metallurgical complex (MMC), innovation cannot be viewed as a standalone corporate initiative; rather, it is an emergent property of a complex industrial ecosystem that balances high asset specificity, extreme capital intensity, and prolonged investment horizons [1]. The primary structural impediment identified in the research is the profound misalignment between short-term financial reporting requirements and the long-term lifecycle of core metallurgical technologies.

Unlike light industries or the digital services sector, where the cycle from concept to commercialization can span months, the development and deployment of breakthrough technologies in the MMC (such as direct hydrogen reduction of iron ore or automated deep-level extraction systems) routinely require between seven and fifteen years [5]. This temporal mismatch creates a structural bias toward incremental innovation—such as minor equipment modifications or localized software patches—at the expense of radical, value-generating technological leaps.

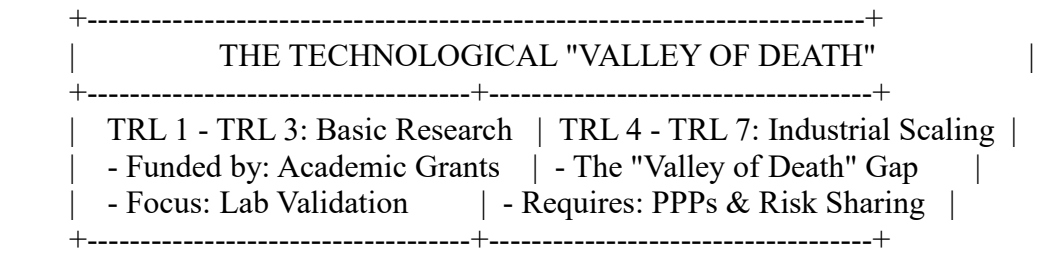
When analyzing capital allocation strategies within major enterprises, it becomes clear that the internal rate of return (IRR) metrics traditionally utilized by corporate financial managers inherently penalize high-risk, long-term R&D initiatives. In volatile commodity markets, where price fluctuations of copper, iron ore, and aluminum can swing corporate revenues by 30% to 40% within a single fiscal year, corporate executives naturally favor capital expenditures that offer immediate, predictable cost-reductions over speculative technological research [3]. Consequently, without external economic mechanisms designed to absorb or offset these structural risks,

innovative activities remain chronically underfunded, often hovering below the critical 0.5% turnover threshold necessary to catalyze industry-wide modernization.

Institutional Frameworks and Public-Private Risk Allocation

To overcome these structural barriers, institutional frameworks must be engineered to redistribute the risk burden between private capital and public institutions. The analysis of leading mining jurisdictions—most notably Australia's Cooperative Research Centres (CRCs) and Canada's Strategic Innovation Fund—provides concrete evidence of the efficacy of structured public-private partnerships (PPPs) in de-risking early-stage industrial research [11]. These frameworks operate on a co-investment model where state funding matches private expenditure, thereby reducing the initial capital exposure for the individual enterprise.

However, the mere injection of public capital is insufficient. The economic mechanism must be structured to address the specific phases of the technology readiness level (TRL) spectrum. The most critical failure point in the MMC innovation lifecycle occurs between TRL 4 (component validation in a laboratory environment) and TRL 7 (system prototype demonstration in an operational environment)—a phase widely designated as the technological "Valley of Death" [9]. Private venture capital is generally averse to funding industrial scale-ups due to the massive physical infrastructure costs involved, while academic grants are strictly confined to fundamental research.



Therefore, an effective economic mechanism must introduce specialized institutional vehicles, such as state-backed industrial demonstration funds or technology guarantee schemes. These instruments act as primary risk-absorbers during the pilot-plant phase. By providing non-dilutive financing or first-loss guarantees for commercial-scale pilots, the state effectively lowers the entry barrier for conservative metallurgical enterprises, accelerating the commercialization of homegrown scientific advancements [2].

Fiscal Levers, Tax Optimization, and Capital Renewal Dynamics

Among the direct and indirect economic mechanisms available to policymakers, fiscal policy remains the most immediate lever for driving corporate technological renewal. The quantitative analysis of capital expenditure trends indicates a direct correlation between the velocity of fixed asset turnover and the availability of targeted tax optimization instruments [4].

Specifically, the mechanism of accelerated depreciation has proven highly effective in transforming corporate balance sheets. In a standard fiscal regime, heavy metallurgical machinery is depreciated over a linear period of 10 to 15 years, matching its physical wear-and-tear. However, in an era of rapid digital obsolescence, the economic utility of automated systems, IoT sensors, and advanced control loops degrades far faster than the physical steel housing them.

By allowing enterprises to utilize accelerated depreciation schedules—writing off up to 100% of the capital expenditure on qualifying innovative technologies within the first 3 to 5 years of operation—the state significantly enhances corporate cash flows [4]. This tax deferral mechanism injects liquidity back into the enterprise precisely when it is needed most: during the post-

implementation phase of a new technology when operational adjustments are being made and full capacity has not yet been achieved.

Furthermore, the structure of R&D tax credits must be refined to reward collaborative innovation rather than isolated internal developments. The research indicates that tax credits that offer an elevated deduction rate (e.g., 150% to 200% of eligible expenses) for R&D conducted in partnership with domestic universities and national research institutes yield a dual benefit [6]. Not only do they lower the net cost of research for the mining enterprise, but they also foster a sustainable pipeline of knowledge transfer, forcing academic institutions to align their scientific output with the concrete practical problems faced by heavy industry.

The Economics of Environmental Compliance and "Green" Metallurgy

Environmental regulations, long viewed by industrial managers as a friction point that increases compliance costs, are increasingly being transformed into a primary driver of technological innovation through market-based economic mechanisms. The introduction of carbon pricing frameworks, such as the European Union's Emission Trading System (ETS) and equivalent national carbon taxation schemes, has structurally altered the cost accounting metrics of metallurgical production [5].

Historically, the negative externalities of carbon-intensive steelmaking and ore smelting—such as greenhouse gas emissions and environmental degradation—were omitted from corporate profit-and-loss statements. Under a robust carbon tax regime, these externalities are internalised into the direct production cost per ton of output. For example, in a conventional blast furnace-basic oxygen furnace (BF-BOF) steelmaking route, the production of one ton of crude steel emits approximately 1.8 to 2.2 tons of carbon dioxide (CO_2). With carbon prices rising globally, these emissions impose a substantial financial liability that threatens the market competitiveness of traditional producers [12].

This financial pressure alters the economic viability of radical alternative technologies. The capital expenditure required to transition to a hydrogen-based direct reduced iron (DRI) process combined with an electric arc furnace (EAF) is undeniably massive, frequently exceeding billions of dollars for a single integrated plant [5]. However, when the long-term cost models incorporate the projected penalties of carbon taxes alongside the premium pricing commanded by "green steel" in international markets, the economic calculation shifts. The payback period for green metallurgical investments compresses dramatically, converting a high-risk environmental initiative into a strategically necessary capital upgrade [12].

CARBON EMISSIONS VS. METALLURGICAL PROCESS	
Blast Furnace (BF-BOF) Route	Hydrogen DRI + EAF Route
- 1.8 to 2.2 tons of CO2 / ton	- Near-zero CO2 emissions
- High Carbon Tax Liability	- High Initial CapEx
- Shrinking Global Markets	- Lowers Long-Term Risk Profile

To support this transition, economic mechanisms must incorporate "green financing" infrastructure. Green bonds and sustainability-linked corporate loans offer innovative enterprises access to capital at a lower coupon rate compared to conventional debt instruments. Financial institutions evaluate the carbon reduction trajectory of the enterprise; if the company successfully hits its technological milestones (e.g., reducing emissions by a defined percentage via innovative carbon-capture or energy-efficiency technologies), the interest rate on the debt drops. This direct

alignment of environmental performance with financial optimization provides a powerful motivational mechanism for corporate directors to aggressively pursue deep technological decarbonization.

Mitigating the "Raw Material Trap" Through Value-Chain Escalation

For resource-rich developing economies, a primary macroeconomic challenge is the "Raw Material Trap"—a structural condition wherein an economy remains trapped in the low-value-added extraction phase of the global value chain, exporting raw ore concentrates while importing high-value finished metal products [7]. Breaking this cycle requires a sophisticated combination of fiscal constraints and innovation incentives designed to force value-chain escalation.

The deployment of simple export bans on raw ore, while politically attractive, frequently results in unintended economic distortions, including sharp declines in state tax revenues and immediate capital flight by multi-national mining corporations. A more nuanced economic mechanism relies on an escalating export tariff structure linked directly to the degree of processing of the material. Raw ores are subjected to maximum tariff rates, while intermediate products (e.g., pellets, mattes, crude blister metals) face lower rates, and fully processed, high-purity metals or advanced alloys are completely exempted from export duties [7].

[Raw Ore Extraction] --> [Beneficiation / Pellets] --> [Finished Alloys]
(High Export Tariff) (Moderate Export Tariff) (Zero Tariff + Subsidy)

To complement these defensive tariffs, the state must deploy offensive incentives that redirect a fixed percentage of mineral extraction royalties directly into a localized processing innovation fund. Instead of disappearing into the general state budget, these royalties are ring-fenced to finance research into local beneficiation (ore upgrading) and refining technologies. This mechanism addresses the specific geological and chemical realities of the domestic ore bodies.

Because every mineral deposit possesses unique mineralogical characteristics, foreign processing technologies cannot simply be imported off-the-shelf; they must be adapted through intensive local metallurgical research [1]. By financing this specialized localized research through royalty reinvestment, the state enables domestic enterprises to build the unique technological capabilities required to profitably process lower-grade or highly complex domestic ores, shifting the country’s role from a passive supplier of raw materials to an active innovator in advanced metallurgy.

Human Capital, Labor Productivity, and Absorptive Capacity

The discussions surrounding innovation in the MMC frequently commit the error of technological determinism, focusing exclusively on hardware procurement and software licenses while ignoring the human element required to operate these systems. The empirical reality is that the efficiency of an innovative activity is fundamentally limited by the "absorptive capacity" of the enterprise's workforce—defined as the collective ability of employees to recognize the value of new information, assimilate it, and apply it to commercial ends [8].

The introduction of Industry 4.0 technologies—such as autonomous haulage fleets, AI-driven predictive maintenance systems, and automated chemical analysis labs—fundamentally transforms the labor profile of a mining or metallurgical enterprise. The demand for traditional, manual labor declines sharply, while the requirement for specialized cognitive labor (e.g., data analysts, automation engineers, remote systems operators) escalates exponentially [10]. If an enterprise implements an expensive digital twin system but lacks the internal engineering expertise to interpret the real-time data streams and adjust production parameters accordingly, the capital investment fails to yield any measurable productivity gains.

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SHIFT IN WORKFORCE LABOR REQUIRMENTS
Traditional Mining Profile	Modern Industry 4.0 Profile
- Heavy manual labor focus	- Focus on data interpretation
- Rigid operational silos	- Cross-functional agility
- High physical risk exposure	- High cognitive skill requirement

To resolve this issue, the economic mechanisms governing innovative activity must include built-in financial provisions for human capital development. Enterprises should be structured to view labor retraining not as a discretionary operational expense to be cut during market downturns, but as a core component of capital investment. State economic policies can support this by allowing human resource development costs related to new technologies to be written off against corporate tax liabilities at an inflated rate [8].

Furthermore, industrial enterprises must actively co-design educational curricula with regional technical universities. By establishing dedicated corporate chairs, joint laboratories, and mandatory student internship programs, a continuous feedback loop is created. This synchronization ensures that the graduate pool possesses the exact competencies required to manage the next generation of metallurgical infrastructure, maximizing the long-term economic return on every dollar spent on technological innovation.

Risk Mitigation and Venture Financing in Conservative Corporate Cultures

The corporate culture within the mining and metallurgical complex is historically conservative, risk-averse, and highly resistant to operational disruption. This cultural inertia is deeply rooted in the physical and economic reality of the industry: a single unplanned shutdown of a blast furnace or a primary grinding mill due to a failed technological experiment can cost an enterprise millions of dollars in lost production revenue per day, alongside posing severe safety risks to the workforce [2]. Consequently, plant managers routinely reject unproven innovative solutions, preferring the security of legacy technologies that are demonstrably less efficient but highly predictable.

Overcoming this cultural resistance requires the implementation of precise internal and external economic mechanisms designed to isolate and mitigate operational risk. Internally, forward-thinking enterprises are restructuring their organizational frameworks to decouple "innovation testing grounds" from the main, high-throughput production lines. This is achieved by investing in small-scale, fully instrumented pilot plants or dedicated modular testing facilities where new technologies can be run in parallel with standard operations without threatening the primary revenue stream [9].

Externally, the development of specialized "mining venture capital" (MVC) networks is essential. Traditional venture capital is structured around the software industry model, expecting rapid scale-ups and low capital intensity. MVC, by contrast, must be tailored to the realities of heavy industry, featuring longer fund lifetimes (e.g., 12 to 15 years) and milestone-based funding tranches linked to successful physical engineering scale-ups rather than user-acquisition metrics [9].

When the state partners with these specialized private funds by providing match-funding or downside loss protection, it creates a robust cushion that absorbs the financial shocks of unavoidable experimental failures. Over time, as successful innovations are safely demonstrated and de-risked within this protected venture ecosystem, they can be confidently integrated into the primary production assets, gradually eroding corporate conservatism and fostering a proactive culture of continuous technological evolution.

Conclusion

Improving the efficiency of innovative activities in mining and metallurgical enterprises is a multifaceted challenge that transcends simple technological adoption. It requires a robust framework of economic mechanisms that align the interests of the state, the enterprise, and the scientific community.

The study concludes that:

- **Direct financial support** should be prioritized for breakthrough technologies (e.g., AI in geostatistics, carbon-free steelmaking).
- **Indirect mechanisms**, such as tax credits and accelerated depreciation, are most effective for incremental improvements and equipment modernization.
- **Integration** of environmental and economic goals through "Green Metallurgy" is the only path to long-term competitiveness in the global market.

By implementing the suggested economic mechanisms, MMC enterprises can transition from being resource-intensive to knowledge-intensive, ensuring sustainable growth in a volatile global economy.

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