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Smart mining - opportunities and challenges for Vietnam's mining industry

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ABSTRACT

The mining industry plays a vital role in socio-economic development, particularly in resource-rich countries like Vietnam. Amid global digital transformation and increasing sustainability requirements, smart mining technologies have emerged as an essential trend to optimize operational efficiency, ensure worker safety, and minimize environmental impacts. This paper presents the concept, benefits, and core technologies of smart mining, while assessing its applicability in Vietnam.

Smart mining involves the integration of advanced technologies, such as the Industrial Internet of Things (IIoT), Artificial Intelligence (AI), Big Data analytics, automation, cloud/edge computing, and virtual/augmented reality (VR/AR) across the entire mining value chain. Key benefits include reduced operational costs, process optimization, increased accuracy in drilling and blasting, predictive maintenance, improved talent acquisition, and enhanced occupational safety. Moreover, smart mining supports real-time environmental monitoring, enabling more sustainable and compliant resource extraction.

Vietnam possesses significant mineral resources, including coal, bauxite, iron ore, and rare earths. However, transitioning to smart mining faces numerous challenges: lack of comprehensive planning for resources and infrastructure, outdated technologies and equipment, limited skilled workforce, and an insufficient legal framework to support innovation. In response, the paper proposes a comprehensive set of solutions, including: improving legal and policy frameworks,

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enhancing international and cross-sectoral cooperation, developing digital human resources, piloting smart mining models, and applying digitalization, automation, and data analytics to strengthen management and operations.

The paper concludes that the development of a modern, safe, and environmentally responsible mining sector in Vietnam requires a strategic combination of institutional reform, technological investment, and human capital development. Smart mining is not only a technological solution but also a strategic driver of digital transformation and sustainable growth in the country's mining industry.

Keywords: Digital Transformation, Industrial Internet of Things, Smart Mining, Sustainable Mining, Vietnam Mining Industry

1. Introduction

The mining industry plays a pivotal role in the socio-economic development of nations, particularly in resource-rich developing countries.

The mining industry is a primary source of critical raw materials used across various sectors, including energy, construction, metallurgy, and manufacturing. Minerals such as coal, iron ore, bauxite, copper, rare earth elements, and industrial rocks (e.g., limestone, sand, and gravel) are indispensable to both traditional and emerging industries. These materials form the backbone of infrastructure development and advanced manufacturing processes, particularly in the transition toward high-tech and low-carbon economies.

Mining activities significantly contribute to national Gross Domestic Product (GDP) and generate substantial revenues through taxes, royalties, and environmental fees. In many resource-rich regions, mining remains a cornerstone of the local economy, providing financial resources for public investment in infrastructure, healthcare, and education. The fiscal contribution of the mining sector is especially important in developing countries seeking to diversify their economies and strengthen fiscal capacity.

The mining sector creates direct employment in exploration, extraction, processing, and logistics, as well as indirect jobs in supporting industries. In remote and underdeveloped regions, mining often acts as a catalyst for infrastructure development, urbanization, and poverty reduction. This spatial redistribution of economic activity contributes to reducing regional disparities and enhancing inclusive growth.

Mineral resources, especially energy-related ones, such as coal, oil, and gas, are central to national energy security strategies. Domestic resource development reduces reliance on imports, stabilizes supply chains, and enhances geopolitical resilience. Ensuring long-term availability and accessibility of strategic minerals is vital for sustaining economic development and technological advancement.

In the context of global sustainability imperatives, the mining industry is evolving toward circular economy models. This includes efforts in resource efficiency, waste minimization, rehabilitation of post-mining landscapes, and integration of renewable energy in operations. Sustainable mining practices aim to balance economic benefits with environmental protection and social responsibility.

To achieve sustainable development, the mining industry continuously adopts the latest technologies to increase labor productivity, reduce costs, maximize the recovery of underground resources, ensure occupational safety, and sustainably protect the environment.

The mining sector is a vast industry impacted by increased technology integration in industrial operations. One of the most significant technological transformations in the mining industry is the adoption of smart mining technology based on digital technology. Smart mining operations are projected to triple by 2025, with 25% of mines having deployed autonomous operations by then. According to one estimate, digital transformation initiatives in the mining industry will generate more than \$460 billion in industry value over the next decade (World Economic Forum, 2016). Smart mining technology's evident impact makes it clear that embracing it is the key to the growth for the sector. Smart mining is really an industry of the future (VanECK, 2024), (VDMA Mining Supplement, 2021).

Vietnam is a country with significant mineral potential, especially in coal, bauxite, iron ore, limestone, apatite, and more. Its mining industry, with approximately 15% of GDP, plays an important role in the country's industrialization and modernization efforts. Access to smart mining technologies is an essential requirement for Vietnam to develop an efficient and sustainable mining industry.

2. Smart Mining and Its Advantages

2.1. Concept of Smart Mining

Smart mining refers to the application of modern connectivity technologies in mining operations. Figure 1 illustrates the Smart Mining Cycle, a comprehensive framework that encapsulates the core principles and benefits of smart mining practices. This cycle demonstrates how modern connectivity technologies, such as sensors, cameras, and drones, are implemented to create an interconnected system that links both environmental and operational data streams. The smart mining process begins with the integration of technologies, enabling automated processes that reduce human intervention in routine tasks. These advancements lead to the optimization of mining activities, where efficiency is significantly enhanced.

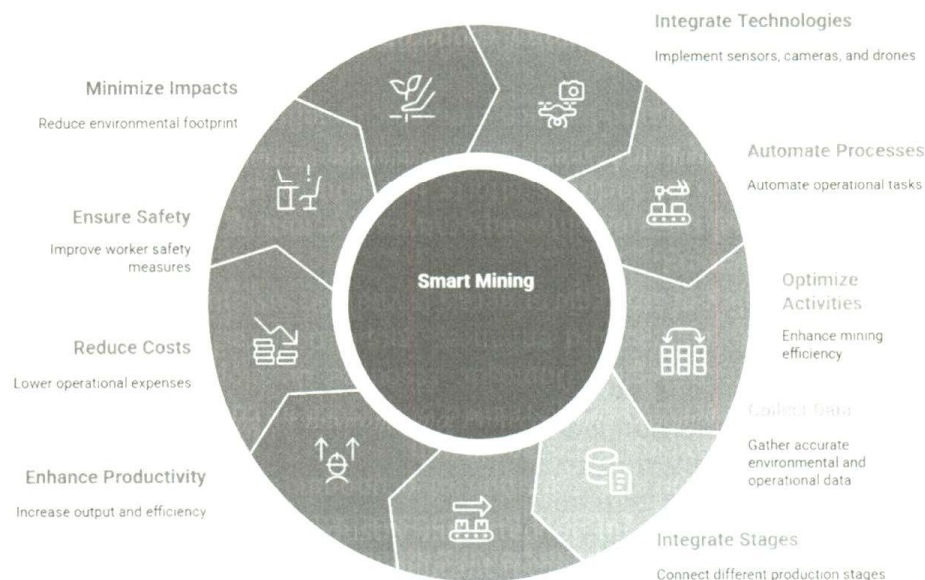


Figure 1. The Smart Mining Cycle: Integrating Technologies for Sustainable and Efficient Mining

Subsequently, the system supports accurate data collection and facilitates the integration of production stages, thereby ensuring operational continuity. This closed-loop system results in measurable improvements in productivity, cost reduction, and worker safety, while also contributing to the minimization of environmental impacts. Altogether, this cycle represents a shift toward sustainable, data-driven, and high-performance mining operations, aligning with Industry 4.0 principles and environmental stewardship.

Figure 2 illustrates the architecture of a smart surface mining system driven by Internet of Things (IoT) networks. On the left, various *Smart Mining Technologies*, including wearable sensors for workers, autonomous haul trucks, environmental monitoring tools, and drones, collect real-time data from the mining environment. This data is transmitted via *connectivity systems* (e.g., wireless networks, satellite links) to a centralized *cloud platform*.

The cloud acts as the core processing and storage unit, enabling remote access, advanced analytics, and decision-making. Processed information is then delivered to multiple *end-user devices*, such as control room monitors, tablets, and mobile interfaces. This interconnected system facilitates continuous monitoring, predictive maintenance, and real-time control, thereby enhancing operational efficiency, safety, and responsiveness in smart mining operations. The figure effectively demonstrates how IoT infrastructure underpins digital transformation in modern surface mines.

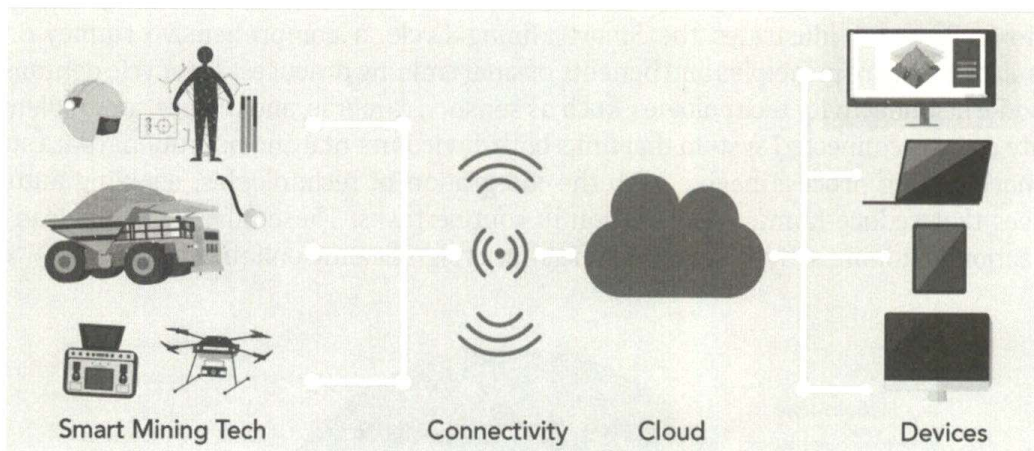


Figure 2. Smart surface mines run on complex IoT networks (Charline Osborne, 2022)

The foundational technology for smart mining is IIoT - a specific application of (Internet of Things) IoT in industrial settings, which enables the connection of devices and sensors to collect and exchange real-time data without manual intervention. IIoT aims to improve production and operational efficiency through comprehensive digitalization.

The implementation of IoT enables the creation of a digital ecosystem where humans, equipment, and vehicles are continuously connected. Data is automatically transmitted among system components, enhancing the capabilities for monitoring, maintenance, and operation of modern machinery. In contrast to traditional manual data collection methods, today's smart devices allow for the real-time gathering of large volumes of accurate data. This data can be processed using AI and Machine Learning (ML) to automate analysis, predict operational

demands, and recommend optimal solutions. This forms the foundation for comprehensive digital transformation and enhances sustainability in the mining industry.

Figure 3 illustrates the system-level architecture and specific applications of IIoT in smart mining. Beyond enabling seamless data transmission, IIoT connects real-time data collection devices with operational equipment and processing systems. Key applications include ore sorting, remote-controlled vehicles, and worker wearables. Once collected, this data is funneled into AI/ML-based processing systems to enable predictive insights and automation. Together, these elements form a tightly integrated ecosystem for next-generation mining operations.

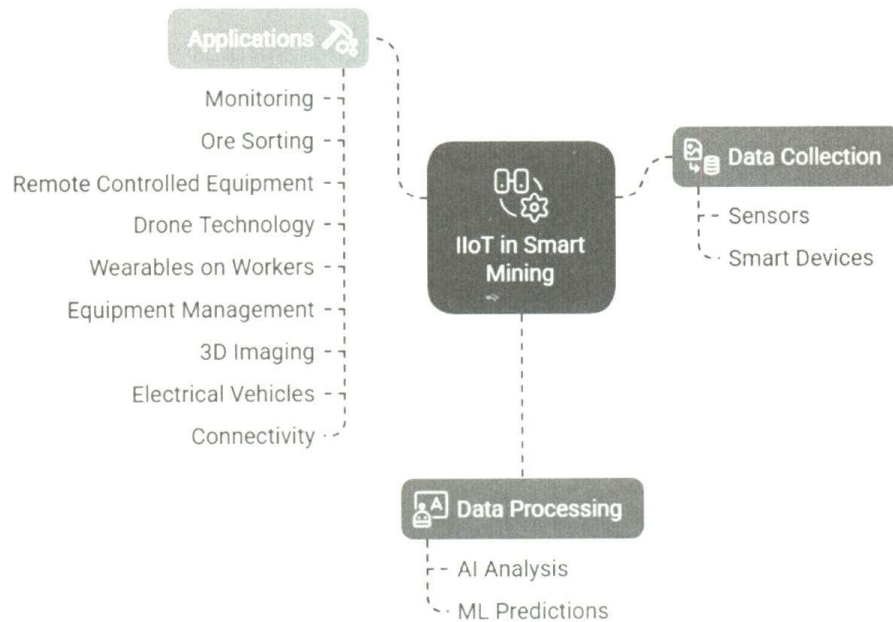


Figure 3. IIoT in Smart Mining: Applications and Benefits

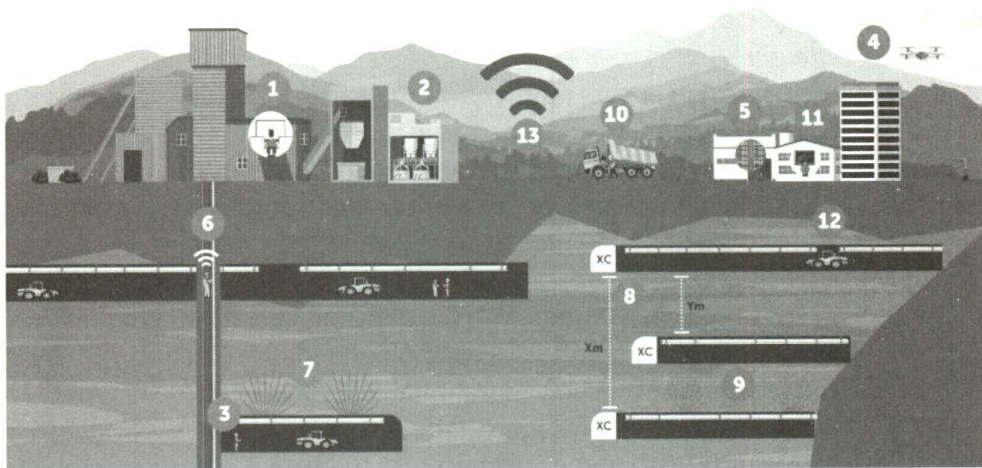


Figure. 4. Applications in Smart underground mines (Yinmaden, 2019)

Figure 4 provides a comprehensive overview of the diverse applications of smart technologies in underground mining operations. It demonstrates how an interconnected digital

mining environment leverages Industrial Internet of Things (IIoT) technologies to enhance safety, efficiency, and automation throughout the mining value chain. Key components include monitoring systems (1), ore sorting facilities (2), and remote-controlled underground equipment (3).

Worker safety is improved using wearable technologies (6), while drone surveillance (4) and 3D imaging (11) provide real-time geospatial data for precise navigation and mapping. The connectivity backbone (13) ensures seamless data exchange between underground and surface-level operations. Advanced data analytics powered by machine learning (5) drive continuous optimization of operational performance.

The figure also highlights modern mining techniques such as sub-level stoping (7), the Variable Cave Production Thickness Method (8), and the Smart Marker System (9) for ore tracking. Autonomous electric vehicles (12) support low-emission transport, while centralized equipment management systems (10) monitor machine conditions and productivity. Altogether, this integrated approach illustrates the future of underground mining, data-driven, automated, and environmentally conscious.

2.2. Advantages of Smart Mining Technologies

The adoption of smart mining technologies yields a wide range of benefits across operational, economic, environmental, and human resource domains. Figure 5 presents a structured synthesis of these advantages, grouped into seven key categories that form the foundation of intelligent, sustainable, and high-performing mining systems.

1. Operational Efficiency

Although the implementation of smart mining systems may require significant upfront investment, their long-term impact on cost reduction and productivity is substantial. Automation reduces the need for manual labor in repetitive or hazardous tasks, while centralized digital infrastructure lowers expenses related to infrastructure maintenance and human supervision. AI-enabled systems allow for real-time decision-making and streamlined workflows, resulting in enhanced efficiency across the value chain.

2. Predictive Maintenance

Smart mining utilizes IoT sensors and machine learning to monitor key equipment indicators, such as temperature, vibration, and pressure, in real time. This enables a shift from reactive to predictive maintenance strategies. By identifying failure patterns before breakdowns occur, companies can schedule repairs proactively, reduce unplanned downtime, extend machinery lifespan, and allocate maintenance resources more efficiently.

3. Data-Driven Decision-Making

The integration of smart mining systems with big data analytics allows for continuous real-time data acquisition and processing. These technologies deliver actionable insights that support informed decision-making at both operational and strategic levels. Whether through enhanced supply chain coordination, fault detection, or optimized resource allocation, data-centric approaches drive agility and competitiveness.

4. Precision in Operations

High-resolution mapping technologies, enabled by drones, LiDAR, and image recognition, provide detailed geological and topographical information, which is critical for accurate blast planning, drilling, and excavation. AI-driven tools reduce human error and optimize the yield

per operation by ensuring that material extraction aligns closely with resource modeling and safety parameters.

5. Occupational Health and Safety

Mining remains one of the world's most hazardous professions. Smart technologies mitigate risks by enabling remote operations and automating dangerous tasks. AI-based safety systems monitor hazardous conditions and trigger alarms or corrective responses. Additionally, wearable devices and Smart PPE (Personal Protective Equipment) allow for real-time tracking of environmental and biometric signals, enhancing responsiveness to emergencies and reducing accident rates.

6. Environmental Stewardship

Environmental risk management is increasingly central to mining operations. Smart technologies facilitate real-time environmental monitoring to detect deviations in water, air, or land quality. AI-driven systems analyze data to predict and prevent potential environmental incidents such as leaks, over-extraction, or habitat disruption. These systems promote energy efficiency, emission reduction, and regulatory compliance, aligning mining with global sustainability goals.

7. Talent Acquisition and Retention

The digital transformation of mining operations is reshaping workforce dynamics. Smart mining not only improves safety but also increases the industry's appeal to younger, tech-oriented talent. By enabling remote operations and interdisciplinary collaboration, it attracts professionals from engineering, data science, and automation, addressing the sector's labor shortages and supporting innovation-driven growth.

As illustrated in Figure 5, smart mining technologies go beyond mere automation, they are strategic enablers of resilient, safe, and sustainable mineral production. The integration of IIoT, AI, and big data analytics forms the backbone of a modern mining ecosystem capable of meeting the demands of a resource-efficient and digitally connected future.

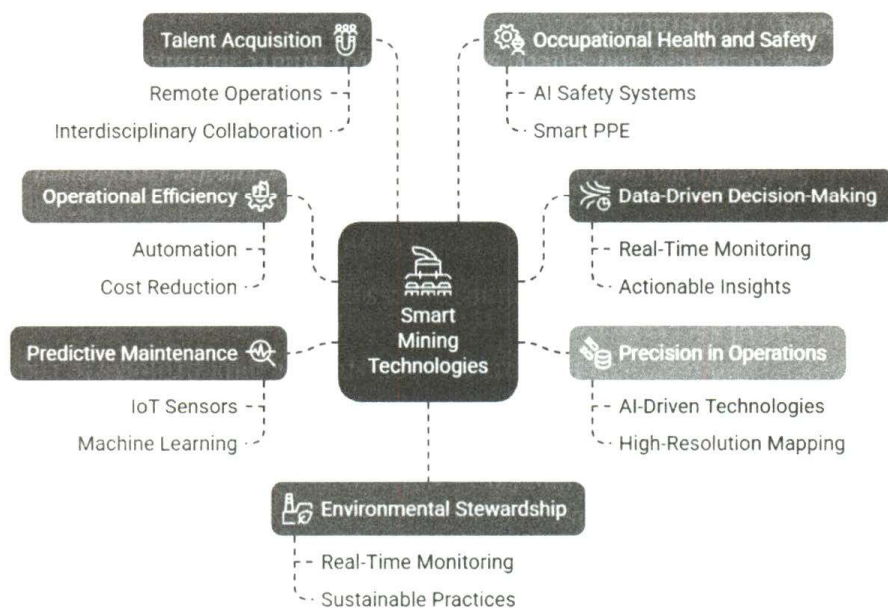


Figure 5. Advantages of Smart Mining Technologies Across Operational and Strategic Domains

2.3. Technologies Applied in Smart Mining

Currently, smart mining technologies are diverse and continuously evolving. However, the commonly applied technologies in smart mining include:

1. *Automation and Remote Control Systems*: for operating machinery such as drills, trucks, and loaders without direct human intervention.
2. *IoT*: for real-time monitoring of equipment, environmental conditions, and production data.
3. *AI and ML*: predictive maintenance, resource estimation, and optimization of operations.
4. *Big Data Analytics*: to analyze vast amounts of operational data for improved decision-making.
5. *Geographic Information Systems (GIS) and 3D Mapping*: for accurate modeling and planning of mining sites.
6. *Robotics*: used in exploration, drilling, and hazardous environments to enhance safety and efficiency.
7. *Drones (UAVs)*: for aerial surveys, monitoring, and inspection of large and hard-to-reach areas.
8. *Digital Twins*: virtual models of mining operations used to simulate and optimize performance.
9. *Blockchain Technology*: to ensure transparency and traceability in mineral supply chains.
10. *Advanced Communication Networks (e.g., 5G)*: to support high-speed, real-time data transmission in remote mining areas.

An example of the application of using smart mining technologies is shown in Figure 6 (Charline Osborne, 2022), in which:

	Stage of the Mining Cycle					
	Prospecting	Mine Design	Mine Construction	Mineral Extraction	Mineral Processing	Monitoring and Rehabilitation
Type of Technology	Underground monitoring systems					
	Autonomous vehicles					
	Remote-controlled drills					
	Unmanned aerial vehicles (UAVs)					
	3D laser scanning					
	Geographic Information Systems (GIS)					
	Image recognition technology					
	Smart PPE					

Figure 6. Smart Mining technology can be deployed at every stage of the mining process (Charline Osborne, 2022)

Monitoring Systems:

A network of IoT-connected sensors is deployed underground (for underground mines) to provide continuous updates on environmental conditions and mining activities. These sensors communicate with each other and with the Internet, enabling data sharing across various devices. Due to the large volume of data collected, organizations often utilize cloud storage to enhance collaboration and optimize management.

Autonomous Mining Vehicles:

While autonomous cars remain under development for mainstream use, self-driving vehicles have already found practical applications in mining. These vehicles autonomously navigate their surroundings, perform material loading and unloading, track optimal routes, and park without human intervention.

Artificial intelligence assists in determining the most efficient travel paths, reducing fuel consumption. Each vehicle communicates with the fleet, and integrated collision avoidance systems increase operational efficiency while minimizing accidents.

Since mining vehicles often operate in hazardous zones, automation reduces risks and enhances worker safety. The large-scale data acquisition from sensors makes smart mining operations significantly more efficient compared to traditional methods. Rich datasets support a deeper understanding of mining processes, thereby improving planning and driving comprehensive enhancements.

Moreover, IoT sensors enable real-time anomaly detection as soon as incidents occur, preventing delayed responses that could worsen the situation. Both surface and underground personnel receive timely alerts, allowing for swift and precise interventions.

Remote-Controlled Drilling Machines:

Drilling rigs operated remotely via control consoles allow workers to avoid direct exposure to drilling hazards. Operators can manage multiple rigs simultaneously, improving overall productivity.

Automated drills also ensure greater precision in borehole creation, minimizing irregular blasting that can complicate material handling and increase operational costs.

Figure 7 presents an expanded landscape of core and emerging technologies that collectively constitute the foundation of modern smart mining systems. These technologies span across automation, data science, spatial intelligence, and human safety, enabling not only operational efficiency but also strategic adaptability and long-term sustainability in mining operations.

Unmanned Aerial Vehicles (UAVs):

Drones are utilized for surveying prospective mining sites and generating detailed visualizations of terrain. Rather than dispatching field teams to physically survey and clear access routes, UAVs provide accurate mapping with resolutions up to one centimeter.

Besides mapping, autonomous drones survey dangerous areas to safeguard workers, assist with inventory management, and conduct routine inspections.

3D Laser Scanning in Mining:

Three-dimensional laser scanning technology, widely applied in civil engineering and architecture, has been adopted in mining to generate precise 3D topographical maps. The resulting data support exploration, drilling planning, and effective project management.

Geographic Information Systems (GIS):

GIS delivers detailed three-dimensional representations of terrain, especially beneficial in inaccessible locations. This technology produces digital maps composed of multiple data layers superimposed over a base map, enabling users to customize views according to specific geographic features.

GIS software facilitates access to maps and spatial databases across various devices and from multiple locations.

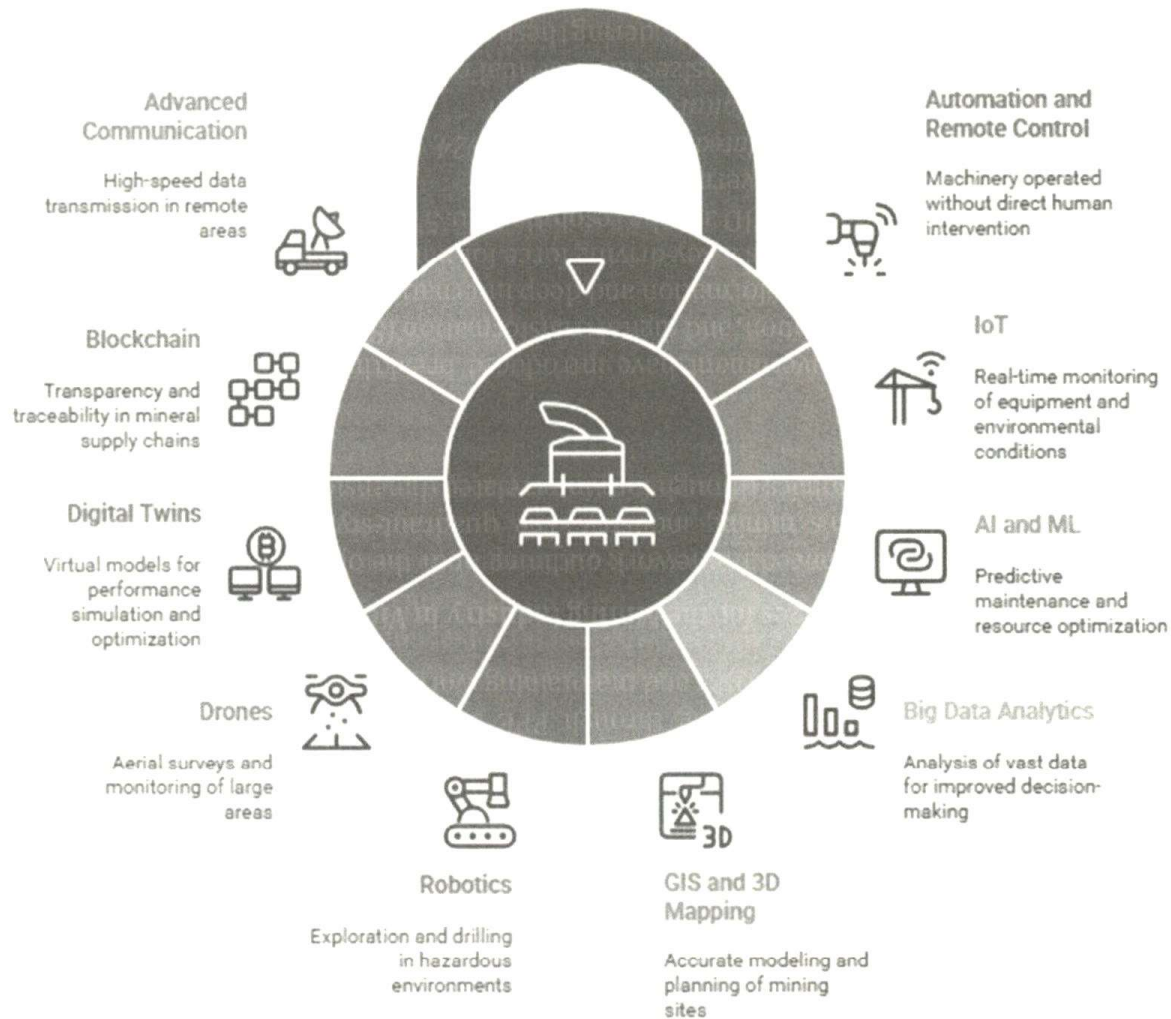


Figure 7. Emerging and Core Technologies in Smart Mining Ecosystems

Image Recognition Technology:

Smart mining employs image recognition to detect ore deposits and distinguish them from surrounding material. This reduces human error and streamlines the extraction process.

Smart Personal Protective Equipment (Smart PPE):

Various personal protective equipment such as helmets, vests, safety glasses, and boots have been enhanced with smart technology. These items incorporate sensors and communication modules that connect workers - particularly those working alone - providing real-time biometric data to ensure safety in hazardous environments.

By monitoring physiological parameters such as body temperature, respiration rate, and heart rate, the system can immediately detect incidents and facilitate prompt emergency responses. Some smart PPE can also identify toxic gases, preventing potentially fatal accidents.

Additionally, biometric monitoring through PPE assists in managing work-rest cycles effectively, reducing overexertion risks and maintaining worker safety.

3. Opportunities and Challenges for the Mining Industry in Vietnam

Figure 8 presents a balanced framework outlining both the opportunities and challenges currently shaping Vietnam's mining industry. The quadrant-style diagram illustrates the sector's developmental dynamics through four interrelated dimensions:

3.1. Opportunities

1. The Party and the Government have introduced breakthrough policies to encourage science and technology, innovation, and digital transformation (STID).

In the context of digital transformation and deep international integration, STID have been identified by the Party and State as a key driving force for national development. Two strategic documents currently related to STID are the resolution No. 57-NQ/TW of the Politburo and the resolution No. 03-NQ/CP of the government.

- Resolution No. 57-NQ/TW dated December 22, 2024, of the Politburo on breakthrough development of STID and national digital transformation

Resolution No. 57-NQ/TW emphasizes the essential role and decisive nature of STID in the national development process, while considering these as strategic opportunities for Vietnam to achieve its goal of becoming a developed and wealthy nation in the new era. Some key points were summarized as follows (Politburo, 2024):

+ Total factor productivity (TFP) will contribute more than 55% to economic growth; high-tech exports will account for at least 50% of total export turnover; the digital economy will contribute at least 30% of GDP; online public services and cashless payments will exceed 80% of total transactions;

+ Research and Development (R&D) investment will account for 2% of GDP, with the private sector contributing over 60%; the budget for STID will be at least 3% of the annual total government expenditure;

+ Develop modern digital infrastructure, mastering strategic technologies such as AI, IoT, big data, cloud computing, 5G/6G, semiconductor technology, quantum computing, etc. Ensure nationwide 5G coverage and build smart cities in qualified localities;

+ Build a unified database; implement an effective digital government, digital society, and digital citizens; position Vietnam among the leading countries in cybersecurity and data protection;

+ By 2045, Vietnam will become a developed, high-income country, with the digital economy accounting for at least 50% of GDP; a hub for digital technology industries in the region and the world; among the top 30 countries globally in STID; with at least 10 internationally standard digital technology enterprises; attracting a minimum of 5 global tech corporations to invest in Vietnam.

- Resolution No. 03-NQ/CP dated January 9, 2025, of the Government on the action program to implement resolution No. 57-NQ/TW

Resolution No. 03-NQ/CP specifies the strategic directions outlined in resolution No. 57-NQ/TW, summarized into some noticable mission groups as follows (Government, 2025):

- + Raise awareness, promote a shift in thinking, create consensus, and political determination across society regarding STID development;
- + Urgently complete the legal framework, remove legal barriers, and create a favorable environment for innovation and enhancing national competitiveness;
- + Increase investment and develop synchronous infrastructure to support STID;
- + Develop and utilize a high-quality workforce with the necessary capabilities to meet the demands of the digital age;
- + Enhance the STID capacity of the business sector, encourage innovation in production and business activities;
- + Expand and deepen international cooperation in the fields of STID.

2. Vietnam is a country with abundant mineral resources, including important and potential minerals such as rare earths, coal, bauxite ore, iron ore, apatite ore, limestone, and construction materials, etc.

3. State-owned corporations, general companies, and private enterprises operating in the field of mineral extraction and processing in Vietnam have begun to shift their mindset toward sustainable mining. They have gradually invested in advanced equipment and technology, especially Industry 4.0 technologies.

3.2. Challenges

1. Vietnam still lacks comprehensive planning for resources, reserves, land, and infrastructure in a systematic and strategic manner to develop large-scale mining and processing complexes that would enable the use of high-capacity equipment and promote mechanization and automation.

2. Most mineral mines in Vietnam are currently small- or medium-sized; mining conditions are becoming increasingly difficult; safety and environmental protection requirements are becoming more stringent; equipment used is often outdated, posing risks to safety and the environment.

3. Many mines have not paid sufficient attention or invested adequately in research and development, scientific and technological application, or innovation to support mining activities. There is still a lack of technologies and equipment to build operational systems and management processes for smart mining.

4. The human resources needed to implement technologies for smart mining are still limited; time is required for training, capacity building, and mastering the technologies and equipment necessary for the operation and management of smart mining activities.

Overall, while Vietnam's mining industry benefits from progressive policy frameworks and digital transformation efforts, it continues to face structural constraints such as low R&D spending and the dominance of under-resourced small-scale operations. Addressing these imbalances is key to unlocking the sector's full potential in the era of Industry 4.0.

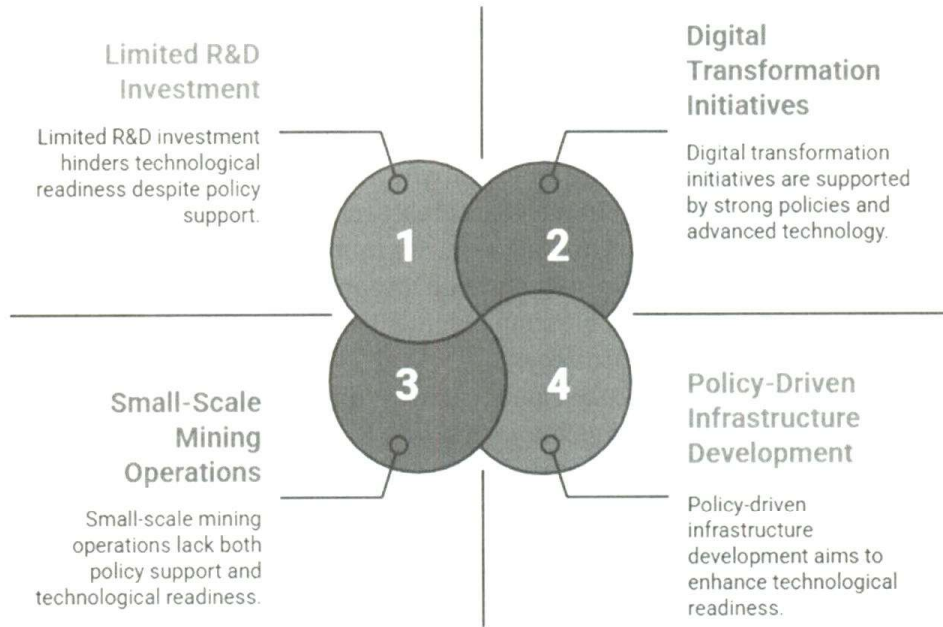


Figure 8. Opportunities and Challenges in Vietnam's Mining Industry

4. Solutions for Developing Smart Mining in Vietnam

The outlines a dual-framework approach for advancing smart mining development in Vietnam is presented in Figure 9, categorized into two primary solution domains: Technical and Technological Solutions and Management Solutions. On the technical side, the focus lies in adopting advanced technologies such as automation, IoT, AI, and GIS to modernize mining operations. This includes upgrading equipment, digitalizing production processes, and enhancing data infrastructure for real-time monitoring and predictive analytics. On the management side, institutional reforms are emphasized, ranging from policy harmonization and workforce training to restructuring governance models and fostering inter-agency coordination. These solutions aim to create an enabling environment for technology adoption and ensure sustainable, regulated growth of the sector.

4.1. Management Solutions

Based on Vietnam's current context in terms of institutional mechanisms, policies, infrastructure, human resources, and the practical conditions of state-owned and private corporations and companies, the following management solutions are proposed to promote the development of smart mining in the country:

1. Improving the Legal Framework and Supportive Policies

Develop and update policies and legal regulations related to smart mining, digital technology, and digital transformation in the mining sector to establish a transparent and enabling legal environment for enterprises.

Encourage investment in research and the application of new technologies through financial incentives, tax relief, and funding support for businesses and research organizations involved in developing smart mining technologies.

Establish specific technical and safety standards for smart mining technologies to ensure consistency and safety in operations.

2. Enhancing Intersectoral Coordination and International Cooperation

Promote coordination among ministries, sectors, and localities in formulating and implementing programs for smart mining development.

Encourage partnerships between universities, research institutes, and mining enterprises to foster research, technology transfer, and high-quality human resource training.

Expand international cooperation with foreign organizations, companies, and research institutes to acquire advanced technologies, management experience, and specialized training.

3. Developing a Human Resource Strategy

Provide training and improve professional capacity for technical and managerial staff in mining enterprises, focusing on digital technologies, IoT, AI, and automation.

Develop multi-level training programs, ranging from short-term courses on operating smart equipment to advanced education in mining technology research and development.

Encourage the attraction of domestic and international talents, creating favorable conditions for high-tech experts to work and collaborate in Vietnam.

4. Strengthening Data Management and Comprehensive Digital Transformation

Develop centralized and secure data management systems to ensure effective collection, storage, and analysis of mining data.

Apply comprehensive digital transformation solutions within mining enterprises to enhance managerial capacity, operations, and data-driven decision-making.

Establish standardized procedures and criteria for data collection, sharing, and utilization among stakeholders.

5. Establishing Evaluation and Monitoring Mechanisms

Develop technical, economic, and environmental evaluation criteria for smart mining technology implementation projects.

Conduct regular inspections and monitoring of technology deployment to ensure compliance with regulations and achievement of intended goals.

Encourage feedback and continuous improvement based on evaluation outcomes to refine technologies and operational methods.

6. Promoting Pilot Models and Scaling Up

Select mines with favorable conditions to pilot smart mining technology solutions, enabling real-world effectiveness assessments.

Establish financial and technical support mechanisms for pilot projects to reduce risks and enhance the likelihood of success.

Replicate successful models in other mines across corporations, enterprises, and the entire industry.

4.2. Technical và Technological Solutions

To enable the application and development of smart mining in Vietnam, the following technical and technological solutions should be prioritized:

1. Digital Transformation and Development of Smart Resource and Environmental Management Systems

Digitize all mine-related data (reserves, geology, current operations, equipment, personnel, environmental data, etc.) to create a centralized database for operational management.

Implement Enterprise Resource Planning systems and Smart Mining Operation Management Systems.

Utilize Geographic Information Systems (GIS) integrated with satellite data and drone imagery for data collection and real-time monitoring of mineral distribution, terrain changes, geological structures, and environmental conditions.

Deploy automatic environmental monitoring stations to measure and alert for air pollution, noise, and wastewater to ensure compliance with environmental regulations.

Develop intelligent waste management systems that integrate the collection and treatment of solid and liquid mining waste, as well as recycling technologies to reuse waste as auxiliary materials.

2. Application of IIoT and Smart Sensors

Install IoT sensor systems for continuous monitoring of temperature, humidity, toxic gases, pressure, vibration, and movement within mines. Develop diverse wireless sensor networks using specialized sensors (e.g., CH₄, CO, CO₂ gas sensors; humidity, temperature, pressure, vibration, and dust sensors) to monitor working conditions in real time. These networks should be self-configuring, fault-tolerant, and provide full coverage in complex underground environments.

Connect sensors to communication networks to create an automated monitoring network that supports early warning and rapid decision-making.

3. Automation and Robotics in Mining Operations

Deploy autonomous machinery and equipment such as self-driving trucks, remotely operated drilling machines, and smart conveyors to minimize human exposure to hazardous environments.

Integrate Supervisory Control and Data Acquisition (SCADA) systems across all mining and transportation processes for enhanced monitoring, safety, and operational optimization.

4. Development of Reliable Communication and Connectivity Systems

Establish high-security, dedicated communication networks using fiber optics and private 5G systems in mining areas to ensure high-speed, low-latency, and secure data transmission. Design redundant and self-healing communication systems to prevent data loss in challenging terrains and harsh weather conditions.

Apply advanced cybersecurity measures such as data encryption, access control, and intrusion detection to protect systems from cyber threats.

5. Development of Big Data, AI, and ML Platforms

Collect and integrate multi-source data from IoT sensors, automated devices, surveillance cameras, digital geological maps, and management systems to build a comprehensive data repository.

Analyze Big Data from sensors and equipment to optimize the production chain.

Apply ML and AI models to predict safety risks such as subsidence, accidents, gas leaks, collapses, and equipment failures, enabling predictive maintenance and proactive responses.

Use optimization algorithms to plan mining schedules, allocate human resources, and manage equipment to reduce costs and increase operational efficiency.

6. Application of Cloud and Edge Computing

Use cloud computing platforms to store large datasets, enabling scalable, flexible access from various locations and supporting faster remote decision-making.

Deploy edge computing devices near data sources (i.e., at the mine site) to process critical information locally, reduce latency, offload cloud systems, and enhance reliability in mine environments.

Develop integrated systems that synchronize edge and cloud computing platforms to optimize data management and processing.

7. Application of 3D Simulation, VR and AR

Create 3D spatial and terrain simulations of mine sites for design planning, safety training, and emergency drills.

Combine AR with real-time sensor data to provide intuitive visualizations for engineers and managers during field inspections or remote operations.

Build simulation models of mining processes to test operational scenarios and assess technical and environmental impacts before implementation.

Use VR/AR technologies to create realistic 3D training environments for operational skills, incident response, and emergency drills without real-world risks.

8. Development of Energy-Efficient and Environmentally Friendly Mining Equipment

Research and adopt advanced machinery technologies to improve mining efficiency and reduce energy consumption.

Promote the use of renewable energy sources such as solar, wind, and bioenergy to partially power mining activities. Use solar and wind power at remote sites or locations with limited access to the electricity grid.

Implement emission control technologies for gases, dust, and other pollutants to minimize environmental impact. Adopt energy-saving and eco-friendly equipment to reduce operational costs and emissions.

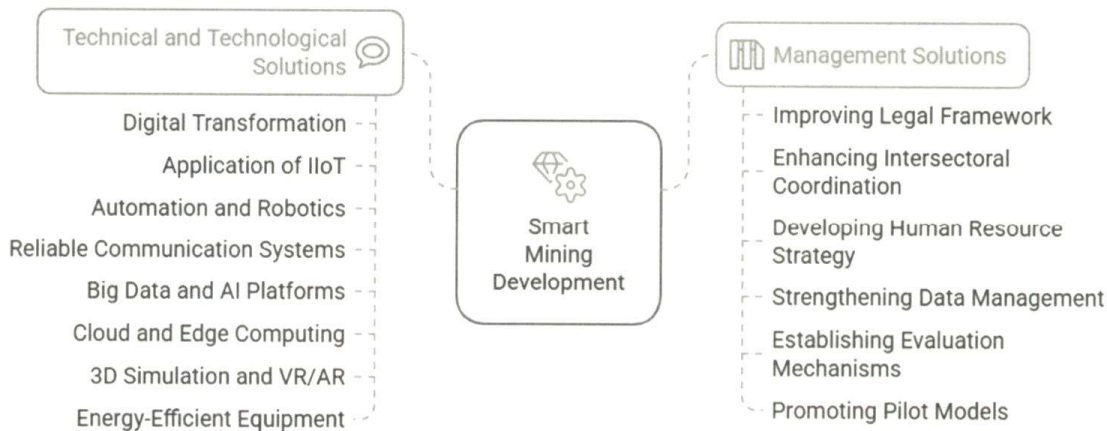


Figure 9. Solutions for Developing Smart Mining in Vietnam

5. Conclusions

The global mining sector is undergoing a profound digital transformation, with smart mining emerging as a strategic response to persistent operational inefficiencies, occupational hazards, and environmental challenges. In Vietnam, where mining plays a critical role in economic development, the adoption of smart mining technologies is not only a timely necessity

but also a strategic opportunity to leapfrog into a more sustainable and efficient industrial paradigm.

This paper has examined the foundational principles, technological pillars, and potential benefits of smart mining, while contextualizing them within Vietnam's specific industrial landscape. Favorable policy frameworks, rich mineral reserves, and rising investment momentum from both public and private sectors provide a strong basis for progress. Nonetheless, challenges persist in the form of fragmented infrastructure planning, outdated equipment, and significant gaps in technological competencies.

To overcome these barriers, a dual-pronged approach combining robust governance mechanisms with targeted technological interventions is essential. This includes strengthening legal and institutional frameworks, fostering cross-sector and international partnerships, enhancing workforce capacity, and initiating pilot programs to validate scalable smart mining models. Technologically, emphasis must be placed on deploying integrated digital platforms, real-time environmental sensing systems, autonomous machinery, and AI-powered decision-support tools.

In summary, the transition to smart mining in Vietnam must be pursued as a holistic and iterative process, anchored in innovation, institutional reform, and human capital development. With sustained political commitment, adequate investment, and cross-sector collaboration, Vietnam's mining industry can evolve into a safer, smarter, and more environmentally responsible sector, fully aligned with national goals for sustainable development and digital transformation.

Contributions of authors

Xuan-Nam Bui - conceptualization, reviewing & corresponding; Carsten Drebenstedt, Nguyen Hoang, Nguyen Van Duc, Tran Quang Hieu, Nguyen Quoc Long, Le Ngoc Ninh - writing & editing, supervision.

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