CRITICAL ANALYSIS OF SYSTEMIC RISKS IN UNDERGROUND COAL MINING OPERATIONS – PERSPECTIVES ON THE FUNCTIONING OF THE ROMANIAN MINING SYSTEM

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ABSTRACT: *The paper identifies and analyzes systemic risks and operational vulnerabilities that may generate collective workplace accidents in the underground coal mining sector. The study is based on the premise that mining operations constitute complex socio-technical systems in which the interaction between technological, organizational, and human factors can produce systemic risks with major impacts on worker safety and on the functioning of the Romanian Mining System. The paper examines the main categories of hazards associated with underground coal mining, such as the accumulation of flammable gases (especially methane), coal dust explosions, underground fires, ground collapses, deficiencies in ventilation systems, non-compliance with electrical safety requirements, and failures of technical equipment. These risks are analyzed from the perspective of the chain effects they may generate at the level of the entire mining system, highlighting how a local failure or an operational error can lead to major disruptions in mining activities or even to the total or partial shutdown of the system. The study also evaluates the institutional and organizational mechanisms for preventing and managing emergency situations in mining, including the role of safety regulations, operational procedures, and monitoring systems. In addition, it analyzes the human and organizational factors that can amplify existing risks, such as inadequate training, communication deficiencies, or economic pressures on production. The results highlight the need to adopt an integrated risk management approach, based on the early identification of systemic vulnerabilities and the implementation of effective preventive measures. The conclusions emphasize the importance of modernizing mining infrastructure, strengthening the safety culture, and developing advanced monitoring and control systems in order to reduce the probability of collective accidents and ensure the continuity of the Romanian Mining System's operation.*

Keywords: Critical analysis, Systemic risks, Coal mining

1. INTRODUCTION

Underground coal mining remains one of the most hazardous industrial activities worldwide, characterized by complex interactions between geological conditions, technological systems, and human factors. In Romania, the legacy of extensive coal exploitation – particularly in regions such as the Valea Jiului – has left a mining system that is simultaneously shaped by historical practices and contemporary pressures of economic viability, regulatory compliance, and workforce sustainability. This study, seeks to examine the multidimensional nature of risk within this sector, moving beyond isolated incident analysis toward a systemic understanding of vulnerabilities embedded in operational, organizational, and institutional frameworks. The concept of systemic risk in underground mining encompasses not only immediate technical hazards – such as methane explosions, coal dust ignition, roof collapses, and ventilation failures – but also latent conditions arising from aging infrastructure, insufficient investment, regulatory gaps, and declining human capital. In the Romanian context, these risks are further amplified by the transition from a centrally planned economy to a market-oriented system, which has led to mine closures, restructuring processes, and fluctuating safety standards. Consequently, risk is not merely a function of underground conditions but a product of interconnected subsystems, including governance structures, safety culture, technological adaptation, and economic constraints. This research adopts a critical analytical approach to explore how these systemic risks are generated, propagated, and managed within Romanian underground coal mining operations. It aims to identify key risk drivers, assess the effectiveness of existing safety management systems, and evaluate the extent to which current practices align with international standards. Furthermore, the study addresses the role of institutional actors, policy frameworks, and organizational behavior in shaping risk outcomes, emphasizing the need for integrated risk management strategies that incorporate both technical and socio-economic dimensions. By situating Romanian mining within a broader discourse on industrial risk and resilience, this paper contributes to the understanding of how legacy systems can adapt to modern safety and sustainability requirements. Ultimately, it seeks to provide insights and recommendations that support the development of a more robust, proactive, and system-oriented approach to risk management in underground coal mining. [1-2]

2. CRITICAL ANALYSIS

Critical analysis consists of the following activities:

- identifying coal mines (hard coal and lignite) classified as critical infrastructures with a role in ensuring energy and national security;
- identifying accident risk scenarios;
- assessment accident risk scenarios;
- developing a protection and safety strategy.

2. Identification of Critical Mining Infrastructures

Table 1 lists the critical infrastructures identified within the Romanian Mining System. [3]

Table 1. Critical Mining Infrastructures

Owner / Type of Coal / Location	Responsible Authority	Name of Coal Mine
Valea Jiului Energy Complex (Hard Coal / Hunedoara County)	Ministry Of Energy	1. Lonea; 2. Livezeni; 3. Vulcan; 4. Lupeni; 5. Paroseni.
Oltenia Energy Complex (Lignite / Gorj County)		1. Rosia; 2. Jilt; 3. Motru; 4. Rovinari; 5. Turceni; 6. Isalnita; 7. Craiova II.

2.2. Risk Scenario Identification

The following risk scenario has been identified as having the highest probability of occurrence.

Risk Scenario: Technical Incident → Collective Work Accident in Underground Mining (coal) – Total/partial shutdown of the Romanian Mining System

2.3. Risk Scenario Assessment

Sequential Progression

TECHNICAL INCIDENT → COLLECTIVE WORK ACCIDENT UNDERGROUND MINING (coal):

TECHNICAL INCIDENT → METHANE GAS ACCUMULATION → HUMAN ERROR (electricians / gas workers) → EXPLOSION → COLLECTIVE WORK ACCIDENT → EVACUATION ERRORS (rescuers) → TOTAL / PARTIAL SHUTDOWN OF MINING COAL UNIT → ENERGY INSECURITY → ECONOMIC INSECURITY → NATIONAL INSECURITY → MATERIAL DAMAGES / LOSS OF HUMAN LIVES → STATE OF NATIONAL INSTABILITY

The causes and associated effects of the risk scenario are described in Table 2

Table 2. Causes and Effects

Causes:	Effects
• non-compliance with Occupational Health And Safety regulations; • non-compliance with electrical safety standards; • electrical short circuits; • improperly enclosed electrical equipment; • working in potentially explosive environments under the influence of methane gas; • poor working conditions and inadequate means of work; • harmful and explosive work environments; • non-compliance with labor regulations regarding potentially explosive environments; • poor condition of underground mining installations; • lack of investments; • lack of routine inspections and repairs; • electrical repairs carried out in the presence of methane gas; • negligence and carelessness of electrical/gas personnel; • lack of specialized and/or trained personnel; • lack of communication or poor communication with the local dispatch center; • evacuation personnel not specialized for crisis situations; • absence of work procedures in unsafe conditions (lack of normal operating state); • inadequate procedures in the event of an accident leading to serious damage; • lack of staff training aimed at preventing and eliminating sources of risk.	• loss of human lives; • loss of production; • stop of the coal market; • failure to supply coal to thermal power plants; • significant losses due to the absence of coal; • significant losses due to the electricity system's dependence on coal → stoppage of electricity production; • potential blackout.

Probability determination
In Table 3, the probability level was determined.

Table 3. Probability determination

Level		Probability definition	Periods
	1. Very low	It has a very low probability of occurring. Normal measures are required to monitor the evolution of the event.	over 20 years
	2. Low	The event has a low probability of occurring. Efforts are needed to reduce the probability and/or mitigate the impact produced.	16 – 20 years
	3. Medium	The event has a significant probability of occurring. Significant efforts are needed to reduce the probability and/or mitigate the impact produced.	11 – 15 years
	4. High	The event has a high probability of occurring. Priority efforts are needed to reduce the probability and mitigate the impact produced.	6 – 10 years
X	**5. Very high**	The event is considered imminent. Immediate and extreme measures are required to protect the target, evacuation to a safe location if the impact so requires.	**1 – 5 years**

Gravity (impact) determination
In Table 4, the vulnerabilities, capacities, and capabilities level was determined.

Table 4. Vulnerabilities, capacities, and capabilities determination

Vulnerabilities, capacities, and capabilities	Level
1. Non-compliance with electrical safety regulation:	1. Very low
• negligence at work;	2. Low
• lack of personal and collective protective equipment;	3. Medium
• working in potentially explosive electrical environments under the influence of methane gas;	4. High
• poor working conditions and inadequate work tools; • harmful and explosive working environments; • non-compliance with labor regulations regarding potentially explosive environments.	**5. Very high**
2. Lack or inadequacy of essential actions and activities in underground mining:	1. Very low
	2. Low
• lack of investment in mining machinery and equipment and/or failure to modernize existing ones;	3. Medium
	4. High
• unpredictability of the administrative management system; • the possibility of a coal supply interruption, leading to: ➢ halting the coal market for thermal power plants; ➢ stopping electricity production from thermal power plants; • energy insecurity, leading to economic insecurity, which in turn generates national insecurity.	**5. Very high**
3. Low level of training among mining personnel:	1. Very low
• electricians not specialized for potentially explosive environments;	2. Low
• blasters not specialized for potentially explosive environments;	3. Medium
• mine rescuers;	4. High
• maintenance personnel; • safety and security personnel.	**5. Very high**

In Table 5, the impacts level was determined.

Table 5. Impact level determination

Impacts	Level
1. Major losses caused by the lack of coal.	1. Very low
	2. Low
	3. Medium
	4. High
	5. Very high
2. Significant losses resulting from other systems' dependence on coal.	1. Very low
	2. Low
	3. Medium
	4. High
	5. Very high
3. Potential damage to the underground environment.	1. Very low
	2. Low
	3. Medium
	4. High
	5. Very high
4. Loss of human lives – strong social impacts.	1. Very low
	2. Low
	3. Medium
	4. High
	5. Very high

In Table 6, the gravity (impact) level was determined.

Table 6. Gravity (impact) determination

	Level	Gravity (impact) definition
	1. Very low	The event produces a minor disturbance in the activity, without material damage.
	2. Low	The event causes minor material damage and limited disruption to activity.
	3. Medium	Injuries to personnel, and/or certain losses of equipment, utilities and delays in providing the service.
	4. High	Serious personnel injuries, significant loss of equipment and facilities, delays and/or interruption of service provision.
X	**5. Very high**	The consequences are catastrophic resulting in deaths and serious injuries to personnel, major losses in equipment, facilities, and termination of service provision.

Risk determination

In the matrix below, the calculation of the risk level can be observed, which is the product of probability and gravity (impact).

PROBABILITY						
	Very high 5					**X**
	High 4					
	Medium 3					
	Low 2					
	Very low 1					
	0	**Very low 1**	**Low 2**	**Medium 3**	**High 4**	**Very high 5**
GRAVITY (IMPACT)						

Calculated risk level		
	Level	Score
	Very low	1 – 3
	Low	4 – 6
	Medium	7 – 12
	High	13 – 16
X	**Very high**	**17 – 25**

The risk scenario has the risk level **25 – Very high (Probability 5 x Gravity/Impact 5)**, and for this reason the risk is being treated with proposed recommendations (measures).

Risk treatment
In Table 7, is proposed mesures.

Table 7. Proposed measures

Vulnerabilities, capacities, and capabilities	Proposed measures
1. Non-compliance with electrical safety regulation.	- strict compliance with occupational health and safety (OHS) regulations; - strict compliance with electrical safety regulations; - supplying and equipping underground personnel with individual and collective work equipment; - immediate cessation of work in the event of a potentially explosive environment.
2. Lack or inadequacy of essential actions and activities in underground mining.	- massive and urgent investments in machinery and equipment and/or the modernization of existing ones; - predictability of the administrative management system.
3. Low level of training among mining personnel.	- Specialized training for maintenance, gas, and rescue personnel; - Investigation of technical incidents and workplace accidents, etc.; - Maintaining installations at an optimal level of operation.

After implementing risk mitigation measures, it results that, according with Table 8.

Table 8. Measures after risk treatment

Impacts	Identified	After the implementation of measures
1. Major losses caused by the lack of coal.	1. Very low	1. Very low
	2. Low	2. Low
	3. Medium	**3. Medium**
	4. High	4. High
	5. Very high	5. Very high
2. Significant losses resulting from other systems' dependence on coal.	1. Very low	1. Very low
	2. Low	2. Low
	3. Medium	**3. Medium**
	4. High	4. High
	5. Very high	5. Very high
3. Potential damage to the underground environment.	1. Very low	1. Very low
	2. Low	2. Low
	3. Medium	**3. Medium**
	4. High	4. High
	5. Very high	5. Very high
4. Loss of human lives – strong social impacts.	1. Very low	1. Very low
	2. Low	2. Low
	3. Medium	**3. Medium**
	4. High	4. High
	5. Very high	5. Very high

Recalculation of consequences' gravity (impact)

In Table 9, is recalculation of consequences' gravity (impact).

Table 9. Recalculation of consequences' gravity (impact)

Level		Gravity (impact) definition
	1. Very low	The event produces a minor disturbance in the activity, without material damage.
	2. Low	The event causes minor material damage and limited disruption to activity.
X	**3. Medium**	Injuries to personnel, and/or certain losses of equipment, utilities and delays in providing the service.
	4. High	Serious personnel injuries, significant loss of equipment and facilities, delays and/or interruption of service provision.
	5. Very high	The consequences are catastrophic resulting in deaths and serious injuries to personnel, major losses in equipment, facilities, and termination of service provision.

Risk recalculation

In the matrix below, the recalculation of the risk level can be observed, which is the product of probability and gravity (impact).

PROBABILITY	**Very high 5**			**X**		
	High 4					
	Medium 3					
	Low 2					
	Very low 1					
	0	**Very low 1**	**Low 2**	**Medium 3**	**High 4**	**Very high 5**
GRAVITY (IMPACT)						

Recalculated risk level		
	Level	**Score**
	Very low	**1 – 3**
	Low	**4 – 6**
	Medium	**7 – 12**
X	**High**	**13 – 16**
	Very high	**17 – 25**

The risk scenario has the risk level **15 – Very high (Probability 5 x Gravity/Impact 3)**, [4-6]

3. DEVELOPMENT OF THE STRATEGY FOR THE MINES IN THE VALEA JIULUI WITH IMMEDIATE EFFECT AND LONG-TERM IMPACT ON THE NATIONAL MINING SYSTEM.

Main measures:

1. TECHNICAL MEASURES

a) Modernization and technologization of mines:

- Introduction of mechanized equipment (mechanized longwalls, hydraulic supports);

- Automation of extraction and transport processes;
- Use of modern technologies to enhance safety.

b) Ventilation and gas control:

- Implementation of efficient ventilation systems (main and secondary ventilation);
- Continuous monitoring of CH_4 and CO concentrations;
- Installation of sensors and automatic alarm systems.

c) Fire and spontaneous combustion prevention:

- Control of temperature and humidity in galleries;
- Inerting high-risk areas (nitrogen, foam);
- Watering coal to prevent spontaneous combustion (e.g., large anthracite stockpiles).

d) Stability of mining works:

- Support of galleries with: metal frames and hydraulic supports;
- Monitoring of rock mass deformations;
- Use of geotechnical models.

e) Combating coal dust:

- Spraying working faces with water;
- Use of dust removal installations;
- Application of inert dust barriers.

f) Monitoring and digitalization:

- SCADA systems and underground sensors;
- Real-time monitoring of gases, temperature, and ventilation;
- Use of drones and robots in hazardous areas.

g) Securing closed mines:

- Sealing and isolating galleries;
- Water drainage and infiltration control;
- Rehabilitation of affected land.

2. ORGANIZATIONAL MEASURES

a) Occupational Health and Safety Management:

- Implementation of risk management systems;
- Periodic assessment of occupational risks;
- Development of safe work procedures.

b) Compliance with Electrical Safety Standards:

- Identification and assessment of electrical hazards;
- Authorization of electrical personnel regarding Occupational Health And Safety;
- Preparation of a Prevention and Safety Plan.

c) Staff Training:

- Periodic training for: emergency situations and equipment use;
- Evacuation and intervention drills.

d) Personal Protective Equipment:

- Helmets, lamps, breathing apparatus;
- Portable gas detectors;
- Flame-resistant clothing.

e) Legal Compliance and Control:

- Compliance with the Mining Law no. 85/2003 and the Occupational Health and Safety Law 319/2006;
- Prohibition of illegal mining operations (which increase risks);
- Periodic inspections by authorities.

f) Intervention and Rescue Plans:
- Specialized mining rescue teams;
- Equipped with rapid response equipment;
- Existence of plans for: fires, explosions, and collapses.

g) Mine Closure Management:
- Phased planning of mine closures;
- Professional retraining of workers;
- Reduction of social and economic impact as part of the strategy up to 2032.

h) Environmental Monitoring:
- Control of water and soil pollution;
- Management of methane gas;
- Land rehabilitation (reclamation).

3. SAFETY (OPERATIONAL) MEASURES

a) Worker Protection:
- Smart personal equipment: portable gas detectors and underground tracking systems;
- Regular medical check-ups.

b) Work Procedures:
- Work permits for high-risk areas;
- Strict rules: limited access and team-based work;
- Accident simulations.

c) Mine Rescue:
- Fully equipped rescue stations;
- Standardized maximum response time;
- Collaboration with the Emergency Situations Inspectorate.

4. SECURITY MEASURES

a) Physical Security:
- Access control: badges and biometrics;
- Perimeter video surveillance.

b) Critical Infrastructure Protection:
- Armed security for fuel depots and electrical installations;
- Anti-sabotage plan.

c) Cybersecurity:
- Protection of SCADA systems;
- IT backup and redundancy;
- Cybersecurity audits.

4. CONCLUSIONS

The strategic context of the mines in the Valea Jiului must be analyzed in direct relation to Romania's energy security, the energy transition, and the risk of major imbalances in the

National Power System. The situation is one of fragile balance between security and decarbonization.

The strategic importance of hard coal mining in the Valea Jiului:

a) Internal energy source → reducing external dependence:

- The hard coal mines (Lonea, Lupeni, Livezeni, Vulcan) supply the Paroșeni thermal power plant: domestic production ensures partial independence from imports, and there are significant reserves (over 100 million tons exploitable, up to 800 million confirmed);
- Conclusion: coal from the Valea Jiului represents a national strategic reserve resource.

b) Backup capacity role (safety energy):

- Coal-based energy has an essential characteristic: constant production independent of weather conditions (unlike wind/solar);
- During peak demand or crisis periods (cold spells, drought, lack of wind), coal-fired power plants can stabilize the system.

c) Effective contribution (limited, but critical):

- Production in the Valea Jiului is relatively low (e.g. ~1,000 t/day);
- Its contribution to the system has sometimes been small (~1.6%);
- However, its importance is not quantitative, but strategic (a safety reserve).

d) Risk of Energy Crises (Blackouts) and the link to mines:

- Incomplete energy transition: Romania is undergoing an accelerated closure of coal capacities due to EU pressures for decarbonization and the shutdown of mines and coal-fired power plants;
- Major issue: alternative capacities (gas, renewables + storage) are not yet sufficient;
- According to sector statements: there is a risk of a "major blackout" in the National Power System by 2026, and delays in gas power plants worsen the situation;
- Conclusion: rapid elimination of coal without replacement → systemic vulnerability;
- Crises arise from the combination of several factors: a decline in domestic production, increased consumption, dependence on imports, and the volatility of renewables;
- The mines in the Valea Jiului operate as an "energy safety net."

e) Strategic limits of coal in the Valea Jiului:

- Although strategic, coal has major limitations: economic inefficiency (high production costs and low competitiveness compared to other sources) and environmental impact (high CO_2 emissions, incompatibility with EU targets, and limited technical capacity);
- Aging infrastructure and limited production;
- Conclusion: it cannot be a long-term solution, only a temporary / transitional one.

Strategic Conclusion:

- The mines in the Valea Jiului play an essential but transitional role;
- They are no longer a primary energy pillar, but remain critical for system security during crisis periods;
- Key idea: Valea Jiului coal = Romania's "energy insurance";
- To avoid blackouts, Romania should adopt a mix of measures:
  - Temporary maintenance of the mines as a reserve;
  - Urgent investments in: flexible gas power plants, stable nuclear, and energy storage (batteries, hydro).
- Mining system in transition (closure + securing): Lonea, Lupeni, Livezeni, Vulcan;

- Funding ~3.9 billion RON for: securing, environmental rehabilitation, and professional retraining;
- Current risks: coal fires and spontaneous combustion, explosions (methane), underground instability, and major social impact;
- The system is no longer just “productive,” but is becoming a system for securing and controlled closure.

5. REFERENCES

[1]. **Daniel Fîță, Sorin Mihai Radu, Marcela Draghilă, Antonia Obreja, Ioan Sima, Cristian Sigheartău, Alin Cruceru, Alexandru Radu**, *Geopolitică, Relații internaționale, Studii de securitate,* Editura Risoprint Cluj Napoca, ISBN: 978-973-53-3386-7, 2025.

[2]. **Fîță, N.D.; Pasculescu D,; Dragoș, P.; Ilieva, O.M.; Gabriel, P.F.; Teodora, L.; Alin, C.E.; Cristian, L.D.; Gabriela, S.; Eugen, S.G.; Mihai, Ș.A.** *Vulnerability and Risk Management to Ensure the Occupational Safety of Underground Mines.* Eng 2025, 6, 88. doi: 10.3390/eng6050088, 20

[3]. **Pasculescu Dragos, Niculescu Titu, Pana Leon**, "*Uses of Matlab software to size intrinsic safety barriers of the electric equipment intended for use in atmospheres with explosion hazard*", International Conference on Energy and Environment Technologies and Equipment (EEETE'10),“Politehnica” University, Bucharest, Romania Published by WSEAS Press ISSN. Vol. 5095. 1790, 2010.

[4]. Arad Susana, et al. "*Aspects of the electric arc furnace control*", Proceedings of the International Symposium on Advanced Engineering & Applied Management, Hunedoara, Romania, 2010.

[5]. **Riurean Simona, Fîță Nicolae Daniel, Păsculescu Dragos, Slușariuc Razvan,** *Securing Photovoltaic Systems as Critical Infrastructure: A Multi-Layered Assessment of Risk, Safety, and Cybersecurity*, Sustainability, 17(10), 4397, 2025.

[1]. **Pasculescu, D., Riurean, S., Ilieva-Obretenova, M., Lazar, T., Tatar, A. M., & Fita, N. D**., *Intelligent modeling of PV–BESS microgrids for enhanced stability, cyber–physical resilience and blackout prevention*, *Energies*, *19*(1), 148, 2026.