

## PROCESS-ORIENTED ANALYSIS OF URANIUM MINE CLOSURE: ENVIRONMENTAL, SOCIO-ECONOMIC AND ENERGY SECURITY IMPLICATIONS

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**Abstract:** *Uranium mine closure represents a complex, multi-stage process encompassing technical decommissioning, environmental remediation, and socio-economic adjustment, with impacts extending beyond the mining sector. In countries operating nuclear power plants, such as Romania, the closure of domestic uranium mining activities also affects regional labour markets and long-term energy system configuration. This study assesses the medium- and long-term impacts of uranium mine closure from a process-oriented perspective, focusing on environmental cost internalization, workforce transition, and institutional coordination. The research adopts a mixed-method approach combining documentary analysis of regulatory and strategic frameworks with a quantitative survey conducted among 50 experts in mining engineering, environmental management, and energy-related fields. Descriptive statistical techniques are used to evaluate expert perceptions regarding the effectiveness and coherence of mine closure processes, including environmental protection measures, social compensation mechanisms, and post-closure development strategies. The results show that technical closure and environmental remediation measures are partially implemented and generally aligned with regulatory requirements. However, significant shortcomings persist in labour reconversion programs, inter-institutional coordination, and the integration of mine closure with regional development and renewable energy initiatives.*

**Keywords:** *uranium mine closure; environmental remediation; socio-economic impacts; labour market transition; sustainable mining; post-mining management*

**JEL Classification:** *Q53, Q58, J64, L72*

### 1. Introduction

The management of industrial and mining closure represents a significant challenge for contemporary economies, particularly in sectors characterized by high environmental risk, strategic resource relevance, and long-term socio-economic impacts. Mining activities and uranium mining, in particular, exemplify this complexity due to persistent environmental liabilities, the specificity of the workforce, and the strategic role of uranium within national energy systems. Unlike conventional industrial shutdowns, uranium mine closure cannot be treated as a single technical operation, but must be understood as a multi-stage process involving interconnected technical, environmental, economic, and institutional components [1, 2].

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In recent decades, global uranium demand has experienced renewed interest, driven by the reassessment of nuclear energy as a low-carbon and reliable component of the energy mix. Paradoxically, this trend has coincided with the closure of numerous uranium-mining operations, especially in countries characterized by legacy mining infrastructures and relatively high production costs. This apparent contradiction highlights structural inefficiencies within the nuclear fuel cycle, where upstream extraction activities are discontinued while downstream electricity generation remains operational [3, 4].

Romania represents a relevant case in this context [5, 6]. Although nuclear power continues to contribute significantly to national electricity production, domestic uranium mining activities have been progressively reduced or terminated. As a result, uranium mine closure has generated impacts extending beyond the mining sector, affecting local labour markets, public expenditure, environmental management systems, and national energy security. These effects propagate through economic and institutional linkages, producing cumulative impacts at local and regional scales.

From a process-oriented perspective, uranium mine closure involves a sequence of interrelated stages, including technical decommissioning of mining infrastructure, stabilization and isolation of tailings facilities, mine water treatment, ecological rehabilitation of affected areas, long-term environmental monitoring, and the implementation of social compensation and labor reconversion measures. Each stage entails specific costs, risks, and decision-making requirements, while the overall effectiveness of the closure process depends on the degree of coordination among responsible institutions and stakeholders. Insufficient coordination or delays at any stage may amplify environmental risks and socio-economic losses over time. These stages are typically implemented by different institutions and over long time horizons, which increases the risk of fragmentation and inefficiencies.

The economic dimension of uranium mine closure is particularly important from a resource governance perspective. Closure-related costs extend beyond immediate technical interventions and include long-term expenditures associated with environmental monitoring, health risk management, and social protection for displaced workers. In many cases, these costs are transferred to public authorities, indicating an incomplete internalization of environmental and social externalities generated during the operational phase of mining. This raises fundamental questions regarding responsibility allocation, public finance sustainability, and the adequacy of regulatory frameworks governing the full life cycle of mineral resource exploitation.

Uranium mine closure also has direct implications for labor markets and regional development. Mining regions are often characterized by high occupational specialization and limited economic diversification, which constrains the ability of displaced workers to transition toward alternative economic activities. In the absence of coherent labour reconversion and regional development strategies, mine closure may lead to persistent unemployment, demographic decline, and reduced local economic resilience.

Another critical aspect concerns energy security. For countries operating nuclear power plants, the continuity of the nuclear fuel cycle represents a strategic objective. The closure of domestic uranium mining operations increases dependence on imported raw materials and exposes energy systems to external price volatility and geopolitical risks. While international uranium markets may offer short-term supply stability, long-term reliance on imports may reduce national energy autonomy and policy flexibility.

Despite the extensive literature addressing technical and environmental aspects of mine closure, limited attention has been paid to uranium mine closure as an integrated, multi-stage process with systemic economic and energy implications. Existing studies frequently focus on isolated components, such as remediation technologies or social compensation mechanisms, without adequately addressing interactions among closure-related processes and their cumulative impacts, particularly in post-socialist economies [5, 6].

In response to this gap, the present study adopts a process-oriented analytical framework to examine uranium mine closure as a complex system of interrelated processes. The main objective of this study is to assess the environmental, socio-economic, and energy security implications of uranium mine closure **in Romania**, with particular emphasis on labor adjustment mechanisms, environmental cost internalization, and policy coordination. By combining documentary analysis with empirical evidence derived from expert perceptions, the study seeks to identify structural weaknesses in current closure management practices and to highlight the importance of coordinated, system-level approaches for enhancing sustainability, resource governance, and long-term resilience.

## 2. Literature Review

The closure of mining activities has been extensively discussed in the literature as a critical phase of the mining life cycle, with implications extending well beyond the cessation of extraction operations. Mine

closure is increasingly recognized as a long-term process that integrates technical decommissioning, environmental remediation, socio-economic transition, and post-mining land use planning [7–9]. In the case of uranium mining, these challenges are amplified by the presence of radiological hazards, long-term environmental liabilities, and the strategic role of uranium within national energy systems.

A substantial body of research focuses on the **technical and environmental aspects** of mine closure. Studies emphasize the importance of stabilizing underground workings, isolating tailings facilities, managing acid mine drainage, and implementing long-term monitoring systems to control radiological and chemical contamination [10–12]. In uranium mining, environmental remediation often extends over several decades, requiring adaptive management strategies and continuous institutional oversight. However, many authors highlight that remediation measures are frequently constrained by limited financial provisions established during the operational phase of mining, leading to the transfer of long-term environmental costs to public authorities [8, 13].

Beyond environmental considerations, the **socio-economic impacts** of mine closure have attracted increasing attention. Mining regions are typically characterized by economic mono-dependence and highly specialized labour markets, which limits their capacity to absorb structural shocks following mine closure [14, 15]. Empirical studies document persistent unemployment, population decline, and reduced regional resilience in the absence of coordinated labour reconversion and economic diversification policies [16, 17]. While social compensation schemes are commonly implemented, the literature suggests that passive support measures alone are insufficient to ensure sustainable post-mining transitions.

In recent years, scholars have emphasized the need to integrate mine closure within broader **regional development and energy transition frameworks**. Post-mining land use options, including renewable energy development, have been identified as potential pathways for revitalizing former mining regions [18, 19]. Solar and wind energy projects, in particular, are frequently proposed for post-mining sites due to the availability of land and existing infrastructure. Nevertheless, the literature indicates that such opportunities are often underexploited due to institutional fragmentation, regulatory barriers, and insufficient coordination between mining, energy, and regional development policies [20].

Another relevant strand of research addresses the **energy security implications** of uranium mine closure. For countries operating nuclear power plants, the discontinuation of domestic uranium mining increases dependence on imported fuel and exposes national energy systems to external market and geopolitical risks [19, 20]. Although international uranium markets provide short-term supply stability, several studies warn that long-term reliance on imports may reduce strategic autonomy and constrain national energy policy options.

Despite these contributions, existing studies tend to analyse mine closure impacts in a **fragmented manner**, focusing separately on environmental remediation, socio-economic adjustment, or energy policy. Relatively limited attention has been paid to uranium mine closure as an integrated, multi-stage process characterized by strong interdependencies among technical, environmental, social, and energy-related dimensions, particularly in post-socialist economies where institutional capacity and financial resources remain constrained [5, 6].

This gap in the literature underlines the need for a **process-oriented analytical approach** capable of capturing interactions among closure-related stages and identifying coordination failures that undermine long-term sustainability. By positioning uranium mine closure as a systemic process rather than a series of isolated technical interventions, the present study contributes to a more comprehensive understanding of post-mining transitions and resource governance challenges in uranium-producing regions.

### 3. Materials and Methods

#### 3.1. Conceptual framework

The complexity of uranium mine closure requires an analytical framework capable of capturing interactions among technical, environmental, economic, and institutional dimensions. Conventional approaches frequently conceptualize mine closure as a terminal phase of mining activity, implemented after resource depletion or loss of economic viability. Such approaches tend to fragment the analysis by treating remediation, labour adjustment, and policy responses as separate and sequential processes.

In contrast, this study adopts a process-oriented conceptual framework that views uranium mine closure as a dynamic system composed of interdependent and partially overlapping stages. This perspective is consistent with process management theory, which emphasizes coordination, feedback mechanisms, and system-level optimization [7, 12, 13]. Framing mine closure as a multi-stage process allows for the identification of critical interdependencies, potential bottlenecks, and leverage points for policy intervention.

The adopted framework recognizes that closure-related decisions generate cascading effects extending beyond the mining sector, influencing local economies, public finance, and national energy systems. Consequently, a systemic analytical approach is required to assess both direct closure costs and indirect, long-term consequences [7].

### **3.2. *Process-oriented model of uranium mine closure***

The proposed conceptual model structures uranium mine closure into five interrelated stages. These stages are not strictly sequential but partially overlapping, with feedback loops linking earlier and later phases. Inefficiencies or delays at any stage may propagate throughout the system, amplifying environmental and socio-economic risks [15, 18]. These stages are used as an analytical structure for both data collection and interpretation of results.

#### **Stage I: Technical decommissioning and physical closure**

This stage involves the decommissioning of extraction infrastructure and the physical sealing of underground and surface facilities. Activities include backfilling or controlled collapse of underground galleries, removal of equipment, securing of mine entrances, and stabilization of structural elements. Although technical closure aims to eliminate immediate safety hazards and prevent uncontrolled contaminant release, inadequate implementation at this stage may increase long-term remediation requirements and associated costs.

#### **Stage II: Environmental remediation and risk mitigation**

Environmental remediation represents the core stage of uranium mine closure due to persistent radiological and chemical risks. This stage includes stabilization and isolation of tailings facilities, treatment of contaminated mine water, soil remediation, and ecological rehabilitation through revegetation and landscape restoration. Remediation is considered a long-term and adaptive process requiring continuous monitoring and periodic reassessment. Where financial provisioning during the operational phase is insufficient, remediation costs are transferred to public institutions, raising fiscal and intergenerational equity concerns [1, 8, 9].

#### **Stage III: Socio-economic adjustment and labor market transition**

This stage addresses the socio-economic impacts of mine closure, with particular emphasis on workforce displacement and labor market adjustment. It includes social compensation mechanisms, retraining and reskilling programs, and measures aimed at promoting alternative economic activities. The effectiveness of socio-economic adjustment depends on synchronization with technical and environmental closure stages and on coordination among mining operators, public authorities, and local stakeholders [7, 16].

#### **Stage IV: Energy system reconfiguration and security management**

Uranium mine closure directly affects national energy systems in countries operating nuclear power plants. This stage captures adjustments within the energy supply chain, including fuel procurement strategies, import dependence, inventory management, and long-term energy planning. From an energy security perspective, mine closure influences supply diversity, exposure to external risks, and strategic autonomy [11, 20]. Integrating energy security considerations into closure planning may enhance system resilience.

#### **Stage V: Post-closure monitoring and institutional governance**

The final stage involves long-term environmental and health monitoring and the establishment of institutional governance arrangements. This includes monitoring protocols, allocation of institutional responsibilities, and financing mechanisms for long-term oversight. Weak governance structures may result in regulatory gaps and underfunded monitoring programs [14, 19]. Post-closure governance functions as a feedback mechanism informing corrective actions across all closure stages.

### **3.3. *Research design and data collection***

The study adopts a mixed-method research design integrating qualitative and quantitative approaches to capture the multifaceted nature of uranium mine closure processes [7, 12]. The qualitative component consists of documentary analysis of policy documents, regulatory frameworks, technical reports, and institutional strategies related to uranium mining and mine closure.

The quantitative component is based on a structured questionnaire administered to 50 experts with professional experience in uranium mining, environmental management, energy policy, and related regulatory fields. A purposive sampling strategy was applied to target respondents with direct involvement in or responsibility for mine closure processes. The sample includes representatives from mining operations, regulatory institutions, technical consultancies, and academic or research organizations.

Although the sample size is limited, it is appropriate for exploratory and descriptive analysis based on expert perception, which is commonly employed in process-oriented studies of complex industrial systems [7].

### 3.4. Survey instrument

The research instrument consists of five closed-ended questions designed to assess key dimensions of uranium mine closure processes. Each question corresponds to one or more stages of the conceptual model and addresses environmental protection, labor market adjustment, regulatory compliance, energy security, and renewable energy policy integration. The survey questions and corresponding variables are summarized in Table 1.

*Table 1. Survey questions and corresponding variables*

Question No	Survey Question	Symbol
1	Have all economic and social aspects been taken into account to protect the environment and the population following the closure of uranium mines?	Q1
2	Do you have information about the main needs of the personnel who will be made redundant following the closure of uranium mines?	Q2
3	Have economic measures been taken to secure the environment?	Q3
4	Is the specific legislation in the field of national security complied with to ensure Romania's energy independence in the event of the decision to close the mines?	Q4
5	Is there a complementary policy to create the premises for increasing the incidence of the renewable energy sector in the context of mine closures?	Q5

Note: The survey questions were designed to capture expert perceptions regarding key stages of the uranium mine closure process, including environmental protection, labor market adjustment, regulatory compliance, energy security, and renewable energy policy integration.

Source: Authors' own survey.

Responses were measured using a binary scale (1 = No; 2 = Yes). This scale was selected to reduce respondent burden and facilitate consistent interpretation of expert assessments. The questionnaire was pre-tested to ensure clarity and relevance.

### 3.5. Data analysis

Data analysis was conducted using descriptive statistical methods, including measures of central tendency (mean, median, and mode), dispersion (standard deviation and variance), and distribution characteristics (skewness and kurtosis). The coefficient of variation was calculated to assess data homogeneity and the representativeness of mean values.

Given the exploratory nature of the study and the limited sample size, the analysis focuses on identifying patterns and tendencies rather than establishing causal relationships. Hypothesis testing is therefore interpreted in a descriptive and associative manner, consistent with the process-oriented scope of the research [12, 13]. Acceptance or rejection of the null hypothesis is based on the coherence and consistency of observed response patterns across the analysed dimensions, rather than on inferential statistical thresholds.

## 4. Results

### 4.1. Overview of Descriptive Results

The empirical analysis is based on responses collected from 50 experts involved in or familiar with uranium mining, environmental management, and energy policy processes. Descriptive statistical indicators provide an overview of expert perceptions regarding the effectiveness and coherence of uranium mine closure processes in Romania.

Across the five analysed dimensions, mean values range between 1.56 and 1.84, indicating that respondents generally acknowledge the existence of closure-related measures while simultaneously expressing reservations regarding their completeness and long-term effectiveness. Dispersion indicators suggest moderate variability in responses, reflecting heterogeneous assessments shaped by respondents' professional backgrounds and institutional roles.

Overall, the results indicate that uranium mine closure processes are perceived as partially implemented and unevenly coordinated, supporting the exploratory nature of the research and justifying a process-oriented interpretation of the findings.

Table 2. Descriptive statistics of survey responses

Variable	Mean	Standard deviation	Variance	Skewness	Kurtosis
Q1	1.84	0.37	0.137	-1.913	1.726
Q2	1.66	0.48	0.229	-0.697	-1.580
Q3	1.78	0.42	0.175	-1.394	-0.061
Q4	1.72	0.45	0.206	-1.011	-1.021
Q5	1.56	0.50	0.251	-0.249	-2.020

Note: The table reports descriptive statistical indicators for the survey responses (N = 50). Responses were measured on a binary scale (1 = No; 2 = Yes). Mean values indicate the central tendency of expert assessments, while skewness and kurtosis describe the distributional shape of the responses.

Source: Authors' own calculations based on survey data.

#### 4.2. Results Related to Technical and Environmental Closure Processes

The first set of results addresses expert perceptions regarding the extent to which economic and social aspects have been considered in relation to environmental protection following uranium mine closure. The mean value recorded for this dimension is 1.84, representing the highest score among all analysed variables.

This result indicates a relatively strong consensus among respondents that environmental considerations have been formally integrated into mine closure decisions. The low variance and negative skewness suggest that a majority of experts perceive environmental securing measures—such as physical sealing of mine workings, tailings isolation, and land rehabilitation—as necessary and largely acknowledged by decision-makers.

However, the concentration of responses toward the upper bound of the scale should not be interpreted as evidence of full effectiveness. Rather, it reflects recognition of environmental protection as a policy priority, without necessarily implying optimal execution or sufficient long-term funding.

#### 4.3. Results Related to Labour Market Adjustment and Social Protection

The second analysed dimension concerns the availability of information and preparedness regarding the needs of workers displaced as a result of uranium mine closure. This variable records a mean value of 1.66, indicating a lower level of agreement compared to environmental protection measures.

The higher dispersion observed in responses suggests uncertainty and inconsistency in the design and implementation of labour reconversion and social compensation mechanisms. While some respondents acknowledge the existence of support measures, others emphasize gaps in workforce retraining, limited employment alternatives, and insufficient integration of displaced workers into new economic activities.

These results indicate that socio-economic transition mechanisms lag behind technical and environmental closure stages.

#### 4.4. Results Related to Environmental Risk Mitigation Measures

The third analysed variable evaluates expert perceptions regarding the adoption of economic measures aimed at securing the environment following mine closure. The mean value of 1.78 indicates a generally positive assessment, albeit with notable reservations.

Respondents acknowledge the implementation of specific remediation measures, including mine water treatment and tailings stabilization. Nevertheless, the observed variability suggests divergent views regarding the adequacy of funding, institutional capacity, and long-term monitoring arrangements.

These findings indicate that environmental remediation processes are perceived as ongoing rather than finalized interventions.

#### 4.5. Results Related to Regulatory Compliance and Energy Security

The fourth dimension focuses on compliance with national security and energy-related legislation in the context of uranium mine closure. The mean value of 1.72 reflects moderate confidence in regulatory adherence, combined with concerns regarding the strategic implications of reduced domestic uranium production.

Experts express awareness of regulatory frameworks governing mine closure and radioactive material management. However, several responses indicate apprehension regarding the coherence between closure decisions and long-term energy security objectives. Increased reliance on imported uranium is perceived as a potential vulnerability for the national energy system.

#### **4.6. Results Related to Renewable Energy Integration and Policy Coherence**

The fifth and lowest mean value (1.56) corresponds to the perceived existence of complementary policies aimed at promoting renewable energy development in regions affected by uranium mine closure.

The relatively high variability reflects fragmented and inconsistent policy implementation. While some respondents identify isolated renewable energy initiatives, others emphasize the absence of a coherent strategy linking mine closure with regional energy transition pathways.

#### **4.7. Synthesis of Results and Hypothesis Assessment**

Taken together, the descriptive results reveal a pattern of partial and uneven implementation of uranium mine closure processes. Environmental and technical closure stages receive comparatively greater attention, while socio-economic adjustment, energy security integration, and renewable energy development remain underdeveloped.

The consistency of these patterns across multiple variables supports the rejection of the null hypothesis (H0) and provides evidence in favor of the alternative hypothesis (H1), indicating an association between the management of mine closure processes and the effectiveness of environmental and socio-economic policy outcomes. These findings provide the basis for a broader interpretation of uranium mine closure as a system of interdependent processes, which is further developed in the Discussion section.

### **5. Discussion**

#### **5.1. Uranium Mine Closure as a System of Interdependent Processes**

The results confirm the central premise of this study, namely that uranium mine closure should be understood as a multi-stage process characterized by strong interdependencies among technical, environmental, socio-economic, and energy-related dimensions. The observed imbalance in the perceived effectiveness of closure-related stages supports the argument that fragmented management approaches undermine the overall sustainability of closure outcomes.

Environmental and technical closure processes receive relatively higher levels of institutional attention, reflecting regulatory imperatives and the public visibility of environmental risks. In contrast, labor market adjustment and energy system integration processes exhibit weaker performance, indicating a predominance of compliance-oriented closure management.

#### **5.2. Environmental Remediation and the Limits of Cost Internalization**

The relatively high scores attributed to environmental securing measures indicate recognition of environmental remediation as a policy priority. Nevertheless, the persistence of variability in expert assessments suggests that remediation processes remain incomplete and financially constrained.

From an environmental economics perspective, these findings highlight the continued challenge of internalizing environmental externalities associated with uranium mining. Reliance on public funding for long-term monitoring reflects deficiencies in financial provisioning during the operational phase and raises intergenerational equity concerns [1, 3, 8, 9].

#### **5.3. Socio-Economic Adjustment as a Structural Weakness**

Lower mean values and higher dispersion for labour-related variables underscore the vulnerability of socio-economic adjustment processes following uranium mine closure. These findings are consistent with the literature on mining-dependent regions, which documents persistent unemployment and economic decline in the absence of coordinated transition strategies [7, 16].

The decoupling of technical closure from labour reconversion initiatives represents a critical coordination failure that limits long-term regional resilience.

#### **5.4. Energy Security Implications**

Moderate confidence in regulatory compliance, combined with concerns regarding strategic coherence, indicates that energy security considerations are insufficiently embedded within mine closure decision-making processes. The closure of domestic uranium mining increases dependence on external suppliers and affects national energy autonomy [5, 11, 20].

Integrating mine closure planning into broader energy system management could mitigate these vulnerabilities.

### **5.5. Missed Opportunities for Renewable Energy Integration**

The weakest performance across all analysed dimensions relates to renewable energy integration. This result highlights a missed opportunity to leverage mine closure as a catalyst for sustainable regional transformation.

Post-mining regions possess significant potential for renewable energy deployment, yet policy fragmentation limits the realization of such synergies [11, 13].

### **5.6. Implications for Process Management and Policy Design**

Overall, the findings emphasize the need for a shift from fragmented, stage-specific closure management toward integrated, system-level process governance. Coordinated interventions across environmental regulation, labour market policy, and energy strategy are essential to improve closure outcomes [7, 12]. These implications provide the basis for the concluding remarks and policy-oriented recommendations presented in the following section.

## **6. Conclusions**

This study examined uranium mine closure as a complex, multi-stage process with significant environmental, socio-economic, and energy security implications. By applying a process-oriented analytical framework, the research moved beyond fragmented, technically focused interpretations of mine closure and highlighted the interdependencies among technical decommissioning, environmental remediation, labor market adjustment, and energy system management.

The results indicate that uranium mine closure processes are unevenly implemented. Environmental and technical closure stages receive comparatively greater institutional attention, reflecting regulatory priorities and risk mitigation requirements. In contrast, socio-economic adjustment mechanisms, energy security integration, and renewable energy development policies remain insufficiently developed. This imbalance generates structural vulnerabilities that may undermine the long-term sustainability of closure outcomes in uranium mining regions.

From an environmental management and resource governance perspective, the findings confirm the persistent challenge of internalizing environmental externalities associated with uranium mining. Although remediation measures are formally recognized and partially implemented, reliance on public funding for long-term monitoring and risk management suggests deficiencies in life-cycle cost allocation and financial provisioning during the operational phase of mining activities.

The analysis also underscores the importance of integrating energy security considerations into mine closure decision-making. The progressive decoupling of domestic uranium extraction from nuclear energy production increases dependence on external suppliers and exposes national energy systems to market and geopolitical risks. Addressing this disconnect requires closer alignment between mine closure planning and broader energy policy frameworks.

A key contribution of this study lies in demonstrating that uranium mine closure should be managed as an integrated system process rather than as a sequence of isolated technical interventions. The process-oriented model developed in this research provides a structured basis for identifying coordination gaps and policy leverage points capable of enhancing environmental sustainability, socio-economic resilience, and long-term energy system robustness.

The study has certain limitations, including reliance on expert perception data and a relatively small sample size. These constraints define the exploratory nature of the analysis but do not diminish its relevance. Future research may extend this framework through longitudinal data, comparative cross-country analyses, or process-based modelling approaches to quantify long-term closure impacts more precisely.

Overall, the findings contribute to the literature on mine closure and mineral resource management by offering an integrated perspective on uranium mine closure. By framing closure activities within broader environmental, socio-economic, and energy systems, the study provides relevant insights for policymakers, practitioners, and researchers concerned with the governance of complex post-mining transitions.

## **7. Policy Implications and Governance Considerations**

### **7.1. Integrating Mine Closure into Strategic Process Management Frameworks**

The findings of this study indicate that uranium mine closure policies should move beyond fragmented, compliance-driven approaches toward integrated process management frameworks. Policymakers should conceptualize mine closure as a long-term, multi-stage process embedded within broader industrial, environmental, and energy strategies.

This requires the adoption of governance structures capable of coordinating closure-related decisions across multiple institutions and policy domains. Establishing inter-ministerial coordination mechanisms or dedicated mine closure management authorities may enhance coherence and reduce institutional fragmentation. From a process management perspective, early integration of closure planning into mining and energy policy design can prevent costly reactive interventions at later stages [7, 12].

### **7.2. Strengthening Environmental Cost Internalization Mechanisms**

Effective internalization of environmental externalities should be prioritized as a core policy objective throughout the mining life cycle. Regulatory frameworks must ensure that financial provisions for closure, remediation, and long-term monitoring are accumulated during the operational phase of uranium mining, rather than deferred to post-closure periods.

Policy instruments such as environmental bonds, dedicated closure funds, or risk-adjusted financial guarantees may enhance fiscal sustainability and reduce the burden on public budgets. Transparent accounting of environmental liabilities and periodic reassessment of closure cost estimates are essential to align private incentives with social welfare objectives [3, 8, 9].

### **7.3. Enhancing Labour Market Transition and Regional Development Policies**

The socio-economic impacts of uranium mine closure underscore the need for proactive labour market and regional development policies. Social compensation mechanisms should be complemented by comprehensive workforce transition programs, including retraining, skill certification, and targeted support for entrepreneurship.

Policies aimed at regional economic diversification should leverage existing industrial infrastructure and human capital in mining regions. Aligning closure timelines with labour transition initiatives may mitigate unemployment risks and enhance the adaptive capacity of affected communities. From a process management standpoint, socio-economic adjustment should be treated as a parallel and integrated stage of mine closure, rather than as a secondary policy response [7, 16].

### **7.4. Aligning Mine Closure Decisions with Energy Security Objectives**

Given the strategic role of uranium in nuclear energy systems, mine closure policies should be explicitly linked to national energy security strategies. Policymakers should assess closure decisions in relation to fuel supply chain resilience, inventory management, and long-term energy planning.

Integrating mine closure considerations into energy policy frameworks may reduce dependence on external suppliers and enhance system robustness. Scenario analysis and strategic foresight tools can support more informed decision-making regarding the timing and sequencing of closure activities [5, 11, 20].

### **7.5. Leveraging Mine Closure for Renewable Energy and Sustainable Transition**

The underutilization of renewable energy development opportunities in post-mining regions represents a missed policy opportunity. Closure planning should incorporate assessments of renewable energy potential, such as solar, wind, or geothermal resources, and explore synergies with existing infrastructure.

Policies promoting renewable energy investments in former mining areas may contribute to local economic revitalization and support broader decarbonization objectives. Integrating renewable energy development into mine closure processes aligns with sustainability principles and enhances long-term regional resilience [11,13].

### **7.6. Improving Institutional Capacity and Long-Term Governance**

Long-term governance arrangements are critical for managing post-closure risks and ensuring regulatory compliance. Policymakers should strengthen institutional capacity for environmental monitoring, data management, and adaptive risk assessment.

Clear allocation of responsibilities among public institutions, stable financing mechanisms, and transparent reporting systems are essential components of effective post-closure governance. From a process-oriented perspective, continuous feedback mechanisms should inform policy adjustments and corrective actions over time [14, 19].

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