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Transforming Mining Regions through Sustainable Redevelopment with Urban Voids and Underground Housing

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Abstract

This paper explores sustainable redevelopment strategies for post-mining regions by integrating urban voids and underground housing solutions. Mining landscapes, often characterized by degraded environments, socio-economic stagnation, and underutilized spaces present significant challenges and opportunities for transformation. Urban voids such as abandoned pits, industrial complexes, and obsolete worker settlements can be repurposed into green infrastructure, public amenities, or residential spaces. Underground housing, leveraging the natural insulation of subsurface environments, offers energy-efficient solutions, while preserving surface land for ecological and communal uses. The research proposes a conceptual framework that combines the adaptive reuse of urban voids with innovative underground housing designs to enhance urban attractiveness, sustainability, and inclusivity. key indexing metrics, including environmental, socio-economic, and urban attractiveness indicators, are developed to evaluate the effectiveness of redevelopment efforts. Case studies from Germany, Belgium, France, and the USA illustrate these strategies' practical applications and transformative potential. The findings emphasize the importance of addressing socio-economic constraints, environmental remediation, and regulatory challenges through participatory planning, innovative governance, and public-private partnerships. The paper concludes by identifying areas for future research, including socio-cultural acceptance of underground housing, region-specific policy frameworks, and advanced remediation technologies. This study provides a comprehensive roadmap for transforming mining regions into vibrant, sustainable, resilient urban environments.

1. Introduction

Mining regions worldwide face significant socio-economic and environmental challenges due to the long-term impacts of extractive activities [1]. These regions, often characterized by abandoned mines, degraded landscapes, and socio-economic stagnation, require innovative strategies to ensure sustainable redevelopment [2-5]. The cessation of mining activities typically leaves behind vast urban voids, such as abandoned pits, disused industrial complexes, and degraded land, creating obstacles to urban revitalization [6-9]. However, these spaces also present unique opportunities for transformation when approached with integrated urban planning and sustainable practices.

The environmental degradation caused by mining activities is a significant obstacle to redevelopment [7-15]. Mining often results in soil contamination, groundwater pollution, and deforestation, making the land unsuitable for conventional uses [1]. Abandoned mining sites frequently pose physical hazards, including unstable structures and residual toxic substances, limiting their potential for reuse [5]. These environmental issues are exacerbated by the socio-economic decline accompanying resource depletion including population outmigration and diminished economic activity [3]. Urban voids in mining regions often disrupt the surrounding urban fabric, creating spatial disconnections and perpetuating socio-economic inequalities [6]. The lack of basic infrastructure such as roads, utilities, and green spaces, further complicates

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redevelopment efforts [16-19]. Consequently, mining regions are often perceived as unattractive and unviable for investment, reducing their potential for economic recovery [6].

Despite these challenges, mining regions possess significant transformative potential. Urban voids, if reimagined, can serve as catalysts for environmental restoration, economic revitalization, and community-building initiatives [16]. Transforming these spaces into multifunctional areas such as green parks, cultural hubs, or Underground Housing Developments (UHDs) can enhance urban attractiveness and foster sustainable growth [9]. Integrating green infrastructure such as urban forests and recreational spaces, mitigates the environmental impacts of mining and improves the quality of life for residents by providing cleaner air and enhanced biodiversity [15]. Underground Housing Solutions (UHSs), leveraging the natural insulation properties of sub-surface environments, offer energy-efficient alternatives to traditional construction and preserve valuable surface land for public amenities or agricultural use [10]. Global examples highlight the potential of mining regions to undergo successful transformation. For instance, the Ruhr Valley in Germany and the Bingham Canyon Mine in the USA have demonstrated how innovative planning and community engagement can turn degraded landscapes into vibrant urban environments [17-19]. These examples underscore the importance of adopting integrated approaches that simultaneously address environmental, socio-economic, and urban design challenges [20-23]. The challenges of abandoned mining sites and urban voids are significant but not insurmountable. Mining regions can transform from degraded landscapes to resilient urban environments by utilizing their inherent potential and implementing creative techniques. To overcome these obstacles and seize these areas' benefits, sustainable redevelopment strategies including incorporating green infrastructure encouraging underground housing, and encouraging community involvement, can be extremely important.

The body of research on post-mining landscapes and urban regeneration highlights various individual strategies to address challenges such as urban voids, environmental degradation, and socio-economic decline. However, there remains a significant gap in integrating these strategies, particularly in combining the redevelopment of urban voids with innovative housing solutions like underground housing. This gap underscores the need for a more cohesive approach to transforming mining regions into resilient, attractive urban spaces.

1.1. Gaps in Addressing Urban Voids

Urban voids, defined as abandoned or underutilized spaces left behind by industrial activities, have been extensively studied for their potential to catalyze urban regeneration [3]. Existing literature emphasizes their transformation into green spaces, public amenities, or cultural hubs to restore urban connectivity and socio-economic vitality [5, 6, 24-27]. However, the research often treats urban voids as isolated entities rather than elements of a broader urban system [28]. This fragmented perspective limits the scope of urban regeneration efforts, as it fails to consider the potential for synergistic interactions between urban voids and other development strategies.

Moreover, while studies have explored various typologies and metrics for assessing urban voids such as their spatial disconnection or environmental degradation [6], they rarely connect these insights to practical, scalable solutions [22, 29-31]. For instance, the role of urban voids as potential sites for innovative housing solutions remains underexplored, particularly in underground housing development [3, 11-17]. Figure 1 depicts the transformation process of mined lands into urban voids and their subsequent reclamation. The top-left section illustrates how parcels of land are fragmented for mining activities, representing the initial phase of resource extraction. The top-right section highlights the post-mining landscape, where exhausted mines transition into urban voids, often characterized by degraded environments and industrial remnants. The bottom section showcases various reclamation techniques, demonstrating how these voids can be rehabilitated into sustainable land uses such as green spaces, urban infrastructure, and underground developments. This visualization underscores the importance of strategic planning and policy interventions in repurposing former mining sites for long-term environmental and socio-economic benefits.

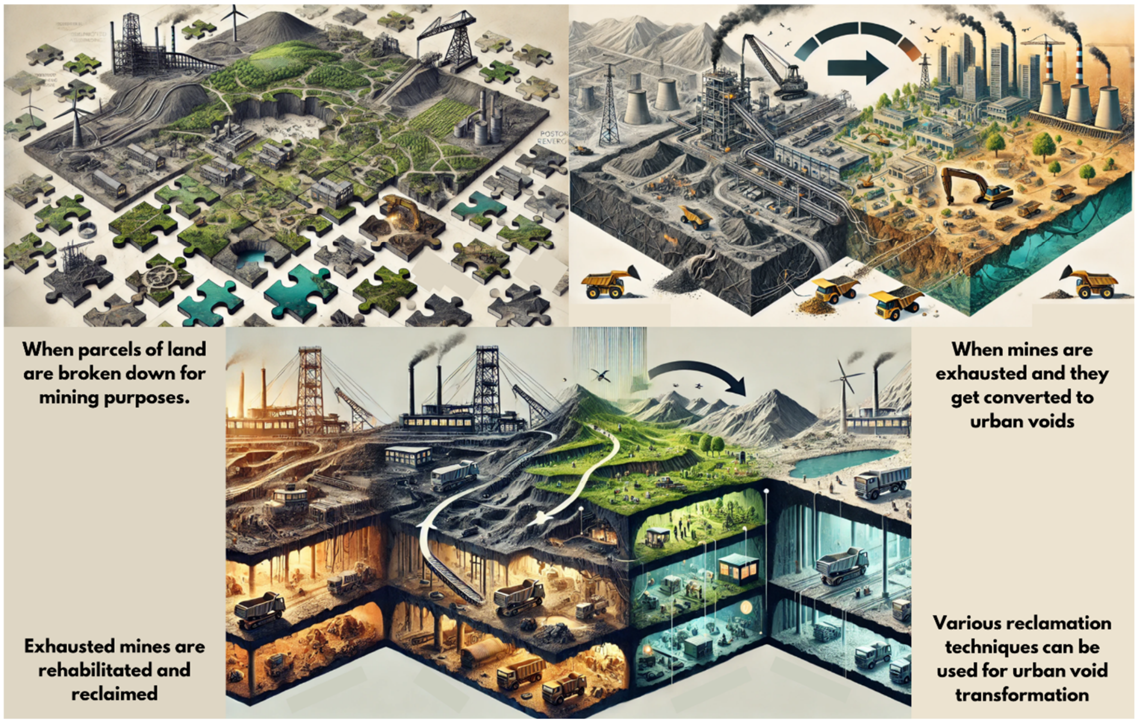

Figure 1. Transformation of mined land into urban voids and their reclamation through various techniques for sustainable redevelopment (Source: Authors).

1.2. Limited Focus on Underground Housing

Underground housing has gained attention for its energy efficiency, land preservation, and ability to address urban density challenges [9; 10]. Research in this area often highlights its thermal advantages, reduced environmental footprint, and potential for integrating renewable energy systems. However, studies frequently focus on its technical and environmental benefits [19, 22, 27, 32-35], neglecting its applicability as part of a holistic urban regeneration framework.

The socio-cultural dimensions of underground housing such as public perceptions [36-38], community acceptance [11, 15-17, 22], and its role in revitalizing degraded areas [27-31] remain underdeveloped in the literature. Furthermore, while some case studies demonstrate the feasibility of underground housing in mining regions, they often fail to link these developments to the broader urban ecosystem, missing opportunities to integrate housing solutions with the reuse of urban voids [11].

1.3. Need for Integrated Approaches

Existing studies on urban voids and underground housing tend to operate in silos, addressing these topics independently rather than as interconnected components of urban regeneration. This separation overlooks the potential synergies between these two strategies. For instance, transforming urban voids into UHDs could simultaneously address challenges related to land scarcity, environmental remediation, and socio-economic revitalization [1]. Moreover, the lack of indexing metrics or frameworks to evaluate the combined impact of urban void reuse, and underground housing hinders the ability of policymakers and planners to assess the effectiveness of such integrated approaches. Metrics such as the Land Utilization Index (LUI) and Thermal Efficiency Score (TES), while relevant, are often applied in isolation rather than within a cohesive framework [5]. The literature reveals a pressing need to bridge the gap between urban void redevelopment and underground housing initiatives. Figure 2 illustrates the concept of urban void redevelopment through underground housing, highlighting its role in addressing land scarcity and optimizing space utilization. The upper section of the figure depicts a reclaimed urban void transformed into green public spaces, promoting land revitalization and environmental remediation. The lower section showcases an underground housing infrastructure for energy efficiency, natural ventilation, and shared spaces, integrating climate-responsive and socio-economic revitalization strategies. The diagram emphasizes the balance between sustainability, space optimization, and repurposing post-mining landscapes for urban resilience.

While both strategies have been explored independently, their integration offers untapped potential for creating sustainable and attractive urban environments in mining regions. Addressing this gap requires the development of comprehensive frameworks and metrics that can guide planners and policy-makers in leveraging the synergies between these approaches. Future studies can then help develop a more comprehensive understanding of how to turn mining areas into habitable and resilient urban areas.

Figure 2. Urban void redevelopment through underground housing as a sustainable solution for land utilization and socio-economic revitalization (Source: Authors).

1.4. Research WORK Objectives

The primary aim of this research work is to explore the transformative potential of mining regions by integrating urban voids and underground housing to enhance urban attractiveness. The study aims to provide a thorough understanding of how these tactics might be integrated to produce post-mining landscapes that are sustainable, habitable, and economically dynamic by filling in the gaps in the literature. Furthermore, this work emphasizes the need for empirical data collection and field-based validation to assess the real-world applicability of the proposed redevelopment strategies. The specific objectives of this work are as follows:

1. **Examine Urban Voids:** Investigate the characteristics, typologies, and potential of urban voids in mining regions, focusing on their adaptive reuse for green infrastructure, public spaces, and residential development.
2. **Evaluate Underground Housing:** Assess the feasibility, benefits, and challenges of underground housing as a sustainable and innovative solution in degraded mining landscapes.
3. **Develop Integrated Frameworks:** Propose a conceptual framework that links urban void rehabilitation with underground housing to enhance urban attractiveness and promote sustainability.
4. **Establish Indexing Metrics:** Create a set of metrics to guide and evaluate redevelopment

projects in mining regions, including indicators for land utilization, thermal efficiency, and socio-economic impact.

5. **Identify Key Indicators for Field-Based Validation:** Define essential parameters for conducting field studies, surveys, and experimental research to empirically validate the effectiveness and adaptability of proposed redevelopment strategies in various mining contexts.

6. **Assess Environmental and Economic Trade-Offs:** Evaluate the cost-benefit analysis and sustainability indexing metrics to measure the long-term financial viability and environmental impact of urban void redevelopment and UHSs.

1.5. Relevance of Case Studies

The selected case studies form the foundation of this research work, illustrating practical applications of the proposed concepts and addressing the identified gaps in the literature. These examples provide insights into the challenges, opportunities, and outcomes of integrating urban voids and underground housing in diverse post-mining contexts. However, while these case studies offer valuable lessons, their success is shaped by various contextual factors including governance structures, socio-economic conditions, environmental constraints, and financial investments. The applicability of these strategies may vary depending on regional policies, community acceptance, and the availability of resources for large-scale implementation. Recognizing these differences is essential for adapting and refining redevelopment approaches to suit diverse mining landscapes.

1. **Ruhr Valley, Germany:** The Ruhr Valley is a prominent example of how abandoned mining landscapes can be successfully repurposed through innovative planning and community engagement. This case study highlights the transformation of urban voids into multi-functional spaces including green infrastructure, cultural hubs, and sustainable housing developments [17]. It provides a blueprint for leveraging industrial heritage and aligning redevelopment projects with community needs.

2. **Bingham Canyon Mine, USA:** As one of the world's largest open-pit mines, the Bingham Canyon Mine demonstrates the potential for large-scale urban voids to be converted into underground housing and green spaces. This case study emphasizes integrating environmental remediation with urban design to create energy-efficient housing while addressing land scarcity challenges [19].

3. **Rochefort, Belgium:** Rochefort's redevelopment efforts showcase the adaptive reuse of mining voids for community-centric developments. The integration of underground housing and public spaces in this region highlights the socio-economic benefits of innovative housing solutions, while preserving the natural environment [10].

4. **Perrier Mines, France:** This case study explores the transformation of volcanic stone extraction tunnels into underground housing and recreational spaces. It underscores the importance of preserving cultural identity, while creating sustainable living environments, offering insights into how industrial legacies can be reimagined for modern needs [11].

These case studies align with the research work objectives, offering diverse perspectives on how mining regions can be revitalized through the dual strategies of urban void rehabilitation and underground housing. Through analyzing these cases, the research work aims to create practical frameworks and solutions that tackle the worldwide environmental, socioeconomic, and urban planning issues that post-mining landscapes face. Figure 3 illustrates the research methodology for analyzing urban void redevelopment through underground housing. The process begins with problem identification and a literature review to define research gaps. It then moves to case study selection and data collection, where specific mining regions are studied for spatial, environmental, and socio-economic data. This is followed by stakeholder consultations to gather community insights and public perception. The framework and metrics development phase formulates an integrated assessment approach validated through comparative analysis. Finally, findings and recommendations are synthesized to guide policymakers and urban developers in sustainable post-mining redevelopment strategies.

2. Urban Voids in Mining Regions

Urban voids refer to vacant, abandoned, or underutilized spaces in urban or peri-urban areas, often resulting from economic and industrial decline. In mining regions, urban voids encompass a range of spaces including disused pits, tailing dams, industrial complexes, and obsolete worker settlements [3]. These spaces present challenges and opportunities for urban regeneration, offering potential for adaptive reuse and sustainable redevelopment [4, 6]. Table 1 summarizes the typologies of urban voids in mining regions, their associated challenges, and potential opportunities for repurposing.

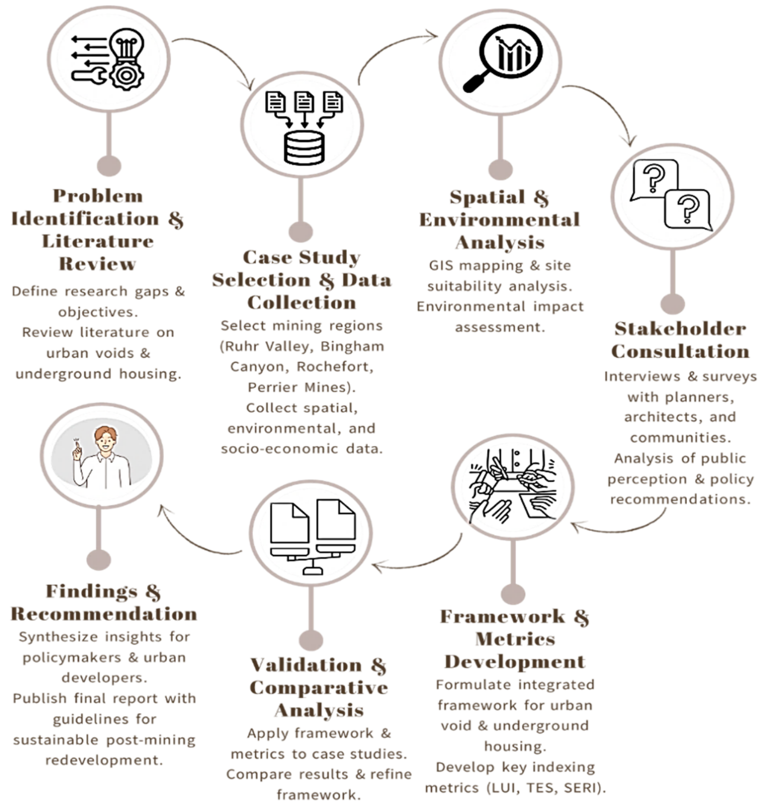

Figure 3. Research work methodology for urban void redevelopment and underground housing analysis (Source: Authors).

Table 1. Typologies, Challenges, and Opportunities of Urban Voids in Mining Regions.

Typology	Description	Challenges	Opportunities	References
Open-Pit Voids	Large excavated spaces left by surface mining operations, often environmentally degraded.	Severe land degradation, contamination, and safety hazards.	Conversion into recreational lakes, parks, renewable energy sites.	[1, 3-5, 7, 9, 11-17, 19-23, 32]
Subterranean Voids	Underground tunnels and shafts created during mining activities.	Unstable ground conditions, lack of accessibility, and safety risks.	Development of underground housing, storage facilities, or tourism infrastructure.	
Industrial Complexes	Abandoned processing plants, warehouses, and mining support facilities.	Contaminated infrastructure, high cost of retrofitting, and limited investment.	Repurposing as cultural hubs, industrial heritage sites, or mixed-use developments.	
Residential Settlements	Worker housing built to support mining activities, often abandoned after mine closures.	Deteriorated structures, social resistance, and insufficient infrastructure.	Rehabilitation for affordable housing, commercial spaces, or community amenities.	
Quarries and Stockpiles	Areas used for material extraction and storage, often with mounds of waste or deeply excavated pits.	Environmental hazards, visual blight, and limited suitability for conventional development.	Transformation into green spaces, ecological reserves, or urban agriculture zones.	

Global Examples of Repurposed Urban Voids

1. **Ruhr Valley, Germany:** Former coal mining voids have been converted into green parks, residential areas, and cultural attractions, such as the Zollverein Coal Mine Industrial Complex [17].
2. **Athabasca Oil Sands, Canada:** Reclamation of mining voids into wetlands demonstrates ecological restoration potential [19].
3. **South Wales, UK:** The Taff Trail integrates abandoned coal mining areas into a recreational and tourism corridor [16-18].
4. **Witwatersrand Basin, South Africa:** Former gold mining spaces have been rehabilitated into green zones and mixed-use developments, addressing housing shortages [4, 16, 20].

Though challenging to repurpose urban voids in mining regions due to environmental and socio-economic constraints, it holds significant potential for sustainable redevelopment. These voids can be turned into lively, welcoming, and visually appealing urban areas by implementing creative techniques like underground housing, green infrastructure, and cultural integration.

2.1. Mine Reclamation and Major Reclamation Techniques

Mining activities often leave behind degraded landscapes, posing significant environmental, economic, and social challenges. Mine reclamation is critical to restoring mined land for productive and sustainable use [39]. Various reclamation techniques have been developed to mitigate the adverse impacts of mining, ensuring land stability, ecological restoration, and economic revitalization [38-40]. This section explores the primary reclamation techniques employed globally and their relevance to the integration of underground housing as a sustainable redevelopment strategy.

1. **L Recontouring and Surface Stabilization:** One of the primary techniques in mine reclamation involves land recontouring, where disturbed land is reshaped to restore natural topography and stability [41-44]. This method prevents erosion, landslides, and water accumulation in abandoned mining pits. Surface stabilization techniques, including vegetation cover and engineered retaining structures, further enhance land durability and usability for future development [39-42].
2. **Revegetation and Ecological Restoration:** Revegetation is an essential component of mine reclamation, facilitating soil stabilization, biodiversity recovery, and carbon sequestration. Native plant species are introduced to degraded mining areas, promoting ecological balance and enhancing landscape aesthetics [42, 44]. Additionally, wetland restoration techniques have been successfully implemented to rehabilitate water-contaminated mining sites, improving water quality and supporting aquatic ecosystems [39, 40].
3. **Backfilling and Controlled Waste Management:** Backfilling involves refilling open pits and underground voids with mine waste, excavated material, or engineered fill to stabilize the land [45-47]. This technique is beneficial in regions where abandoned mines pose subsidence risks, making the land unsuitable for redevelopment. Controlled waste management strategies, including geosynthetic liners and encapsulation of hazardous materials, ensure environmental safety and long-term land viability [30-32, 35].
4. **Water Management and Acid Mine Drainage (AMD) Control:** Post-mining water management is crucial for preventing contamination and ensuring water sustainability [11-14]. Techniques such as passive and active treatment of acid mine drainage, construction of sedimentation ponds, and water diversion systems help mitigate the impact of mining on local water bodies [39-48]. Effective water management is particularly relevant when considering UHDs, as groundwater interactions and drainage systems must be carefully designed to prevent flooding and structural damage [49].
5. **Adaptive Reuse Strategies – Underground Housing as a Reclamation Tool:** While traditional reclamation techniques focus on surface restoration, adaptive reuse strategies offer innovative approaches to mine redevelopment [47-50]. Underground housing presents a viable solution for utilizing abandoned mining voids, mitigating land scarcity, while promoting energy efficiency and sustainable urban expansion [51]. Underground dwelling uses otherwise unused mining sites, lower energy consumption, and lessens the environmental impact by utilizing the thermal insulation qualities of beneath spaces [52-55]. Furthermore, underground developments can support ongoing reclamation initiatives by including green infrastructure, public places, and community facilities and turn former mining sites into habitable and economically active areas [5, 26, 39, 50-53].

Including subterranean dwellings in mine reclamation plans helps with long-term socioeconomic advantages and addressing land rehabilitation issues. Mining areas can be effectively converted into resilient, sustainable communities by combining conventional reclamation techniques with cutting-edge urban planning strategies, guaranteeing that post-mining landscapes meet people's and the environment's demands.

3. Underground Housing in Mining Regions

Underground housing refers to using subterranean spaces for residential development, often designed to address challenges such as land scarcity [3], environmental degradation [28], and urban expansion. In mining regions, these spaces include disused mine shafts, underground tunnels [29-31], and abandoned pits, offering both challenges and opportunities for sustainable urban redevelopment [9, 10] (refer to Table 2).

While underground housing offers transformative potential, it presents significant challenges, particularly in post-mining landscapes [29] (see Table 3).

Table 2. Key Benefits of Underground Housing in Mining Regions.

Key Benefit	Description	Environmental Advantages	Economic Advantages	References
Energy Efficiency	Subterranean environments provide natural insulation, reducing the need for artificial heating and cooling.	Lower greenhouse gas emissions, reduced energy consumption.	Cost savings from reduced energy bills and renewable energy integration.	[3, 7, 9, 28-31]
Land Preservation	Underground construction conserves surface land for public amenities, green spaces, and agriculture.	Minimizes surface-level disruption, enabling ecological restoration.	Enables dual land use, increasing the value of both surface and subsurface development.	
Innovative Design	Subterranean spaces allow for advanced architectural solutions like geothermal systems and water recycling.	Promotes sustainable resource use and reduces waste.	Attracts eco-conscious residents and tourists, boosting local economies.	
Urban Density Optimization	Maximizes urban space usage by integrating surface and subsurface development.	Supports compact urban growth, reducing sprawl.	Creates additional housing options in high-demand areas, increasing property values.	

Table 3. Underground Housing, Challenges and Strategies.

Challenge	Description	Strategies for Mitigation	References
Technical Challenges	Ensuring structural stability in degraded mining terrains with unstable ground and contamination risks.	Conducting thorough geotechnical assessments, employing advanced engineering techniques, and stabilizing subsurface areas.	[1-3, 7, 9, 23-26, 28-31]
Socio-Cultural Barriers	Overcoming public resistance due to negative perceptions of subterranean living, such as claustrophobia or safety concerns.	Community engagement initiatives, education campaigns highlighting benefits, and incorporating cultural design elements.	
Regulatory Constraints	Lack of established building codes or legal frameworks for subterranean construction.	Developing region-specific regulations, streamlining approval processes, and offering incentives for underground projects.	
Accessibility Issues	Designing spaces that are inclusive and accessible to diverse populations, including individuals with disabilities.	Incorporating elevators, natural lighting systems, and accessible entry points to ensure comfort and inclusivity.	

Global examples of underground housing illustrate its feasibility and transformative potential for mining regions:

1. **Rochefort, Belgium:** Repurposed mine voids were developed into energy-efficient underground housing, while preserving surface areas for parks and community facilities. Geothermal systems enhanced sustainability, and the project fostered community inclusivity and tourism-driven economic growth [10].
2. **Perrier Mines, France:** Former volcanic stone extraction tunnels were converted into modern underground housing units. Integrating green infrastructure and eco-tourism elements improved environmental quality and economic viability [11].
3. **Bingham Canyon Mine, USA:** One of the world's largest open-pit mines was transformed into a mixed-use area featuring underground housing and surface-level parks. The development emphasized energy efficiency and community engagement while addressing land scarcity challenges [19].
4. **Freiberg, Germany:** Historical mining sites were revitalized into a cultural and residential hub, integrating underground housing with mining heritage tourism. This approach preserved local identity while supporting economic diversification and energy-efficient living [17].

Though requiring technical and regulatory innovation, underground housing in mining regions offers a sustainable and inclusive approach to urban redevelopment [3, 7, 9, 23-31]. By tackling these issues and utilizing international best practices, mining landscapes can be transformed into thriving, resilient, and energy-efficient urban areas.

4. Integrating Urban Voids and Underground Housing

Integrating urban voids and underground housing provides a holistic approach to redeveloping mining regions, addressing environmental, socio-economic, and spatial challenges [23, 25-28, 32]. This framework combines the reuse of degraded spaces with innovative housing solutions to optimize land use and enhance urban attractiveness (refer to Table 4). However, while these strategies show promise, there is a lack of field studies, surveys, or experimental projects that validate their feasibility in different contexts. Future research should focus on pilot studies to assess the practical implementation of underground housing in post-mining areas and stakeholder perception surveys to evaluate community acceptance and socio-cultural factors affecting redevelopment.

Additionally, while these strategies offer significant sustainability benefits, a lack of comparative cost-benefit analyses limits understanding their economic feasibility. Future studies should incorporate methodologies such as Life Cycle Cost Analysis (LCCA) and Environmental Impact Assessments (EIAs) to evaluate long-term financial and ecological trade-offs. These assessments would provide a clearer picture of the financial viability and environmental performance of underground housing and urban void redevelopment, facilitating informed decision-making for policymakers and developers.

Table 4. Key Components and Benefits for Sustainable Redevelopment Framework.

Component	Description	Key Benefits	References
Urban Voids as Multi-functional Spaces	Transforming urban voids into parks, public spaces, or community hubs.	Enhances livability, promotes social cohesion, and restores ecological balance.	[3-4, 9, 15, 19-23, 32-33]
Underground Housing	Utilizing subsurface spaces for residential development to address land scarcity.	Preserve surface land, reduce energy consumption, and provide innovative housing solutions.	
Land-Use Optimization	Combining above-ground and subterranean development for efficient use of land resources.	Balances surface and subsurface needs, minimizing urban sprawl while maximizing available space.	
Sustainability Focus	Integrating green infrastructure and renewable energy into urban regeneration projects.	Improves environmental health and supports long-term resilience in post-mining landscapes.	

Integrating urban voids and underground housing creates synergies that align with sustainability objectives. These synergies balance environmental preservation, socio-economic revitalization, and urban attractiveness to achieve holistic redevelopment (Table 5). However, there is a gap in empirical validation regarding their long-term effectiveness, necessitating targeted research and on-site trials to test adaptability across different mining landscapes. Moreover, the absence of structured cost assessments and trade-off evaluations limits the ability to fully assess these initiatives' financial and ecological sustainability.

Effective implementation of the proposed integration model requires collaboration among multiple stakeholders, ensuring that redevelopment aligns with community needs, environmental objectives, and economic feasibility. However, a significant limitation is the absence of structured stakeholder engagement studies that measure these redevelopment models' perceptions, concerns, and adaptability in real-world applications. Future studies should incorporate surveys, policy analyses, and experimental projects that examine such transformations' economic, environmental, and social feasibility (refer to Table 6). Furthermore, conducting comparative financial analyses through LCCA would help understand long-term cost implications, while EIA would quantify environmental benefits and potential drawbacks. These assessments ensure that redevelopment efforts are economically viable and environmentally sustainable over time.

Table 5. Synergies, Sustainability Goals, and Economic & Environmental Considerations in Post-Mining Redevelopment.

Synergy	Description	Sustainability Goals	Economic Feasibility & Environmental Costs	References
Environmental Preservation	Urban voids restored as green spaces or eco-parks while subsurface areas are developed for housing.	Reduced carbon footprint, enhanced biodiversity, and improved air and water quality.	High initial investment for land remediation but long-term environmental benefits. Requires ongoing maintenance costs for green spaces.	[15-17, 22, 27-29, 31, 34-40]
Socio-Economic Revitalization	Creation of jobs and affordable housing options through redevelopment projects.	Economic growth, reduced housing shortages, and enhanced quality of life for local communities.	Underground housing has high construction costs but potential long-term savings. Conventional redevelopment may require larger surface land usage and higher infrastructure costs.	
Urban Attractiveness and Livability	Improved aesthetics, integration of cultural elements, and creation of vibrant public spaces.	Increased community engagement, cultural pride, and regional tourism potential.	Underground housing developments are energy-efficient but may require extensive public awareness campaigns. Conventional methods can lead to rapid urbanization but at the cost of land use efficiency.	
Energy and Resource Efficiency	Leveraging underground housing's natural insulation and renewable energy systems.	Reduced energy consumption, greater reliance on sustainable energy sources, and cost savings for residents.	Underground housing reduces heating/cooling costs but has higher upfront investment. Conventional housing may have lower initial costs but higher energy demands.	

Table 6. Stakeholder Roles, Contributions, and Economic & Environmental Considerations in Sustainable Redevelopment.

Stakeholder Group	Role in Redevelopment	Key Contributions	Economic Feasibility & Environmental Costs	References
Government Authorities	Policy development, environmental regulations, and provision of incentives for sustainable development.	Framework for safe and effective redevelopment, infrastructure funding, and public-private partnerships facilitation.	Requires significant initial investment and policy support to incentivize sustainable projects.	[1-5, 7-11, 23-28, 30-33, 40]
Private Developers	Investment in construction and technology for underground housing and urban void rehabilitation.	Innovation in design and engineering, financial backing, and project management expertise.	High construction costs but long-term economic benefits through sustainable infrastructure.	
Local Communities	Participation in planning processes and decision-making to ensure alignment with local needs and preferences.	Knowledge of cultural and social priorities, community acceptance, and long-term project sustainability.	Acceptance of underground housing may require additional financial incentives and community engagement efforts.	
Environmental Experts	Assessment of ecological impact and guidance on sustainable practices for redevelopment projects.	Expertise in remediation, biodiversity conservation, and integration of green infrastructure.	Environmental remediation may involve high initial costs but ensures long-term ecological sustainability.	
Academic Institutions	Research and development of innovative approaches for land use optimization and housing solutions.	Data-driven insights, feasibility studies, and pilot project designs.	Research funding and feasibility studies are crucial for validating economic and environmental sustainability.	

Integrating urban voids and underground housing necessitates a participatory and inclusive governance structure. Collaborative efforts among stakeholders ensure that redevelopment projects are equitable, sustainable, and beneficial for all involved, paving the way for resilient and attractive urban environments in mining regions. However, empirical research, including pilot projects and community response assessments, must refine these strategies for widespread application. Additionally, conducting comparative cost-benefit analyses through LCCA and EIA would strengthen the economic argument for these strategies, ensuring their long-term viability and scalability. Addressing these research gaps will contribute to developing adaptable, scalable, and context-sensitive urban redevelopment models for mining landscapes.

5. Indexing Metrics for Sustainable Transformation

To ensure the redevelopment of mining regions aligns with sustainability goals and addresses the multifaceted challenges of these landscapes, it is crucial to adopt robust indexing metrics. These metrics provide a structured framework to evaluate progress and success, enabling stakeholders to monitor environmental recovery, socio-economic revitalization, and urban attractiveness. These measures help make well-informed decisions by concentrating on quantifiable indicators, guaranteeing that redevelopment projects are efficient, inclusive, and aligned with long-term sustainability.

5.1. Environmental Metrics

Environmental metrics are critical for assessing the ecological health of post-mining landscapes and the success of remediation and redevelopment efforts [15, 19-22, 28-30, 51-55]. Mining activities often leave behind degraded soils, contaminated water, and unstable terrains, prioritizing ecological restoration for sustainable transformation [1] (refer to Table 7).

Applications in Practice

1. **Ruhr Valley, Germany:** A high LUI was achieved by transforming former coal pits into multifunctional green spaces, cultural attractions, and residential areas. This demonstrated the effective reclamation and repurposing of degraded landscapes [38, 51-55].
2. **Athabasca Oil Sands, Canada:** The reclamation of mining voids into wetlands improved the SGQI, highlighting ecological restoration efforts that made the land suitable for biodiversity and recreational use [14-16].
3. **Bingham Canyon Mine, USA:** Integrating underground housing projects with renewable energy systems ensured a high TES, emphasizing energy-efficient living solutions [11-19, 21].

Stakeholders can monitor and verify the ecological results of redevelopment projects by using environmental indicators, guaranteeing the establishment of more sustainable and healthy surroundings for present and future generations.

5.2. Socio-Economic Metrics

Socio-economic metrics evaluate the broader impacts of redevelopment on local communities, focusing on economic growth, employment opportunities, housing affordability, and overall quality of life. Post-mining landscapes often face socio-economic challenges such as unemployment, population decline, and inadequate infrastructure, making these metrics essential for inclusive and sustainable redevelopment (Table 8).

Applications in Practice

1. **Freiberg, Germany:** A high CSI was achieved by integrating mining heritage into the redevelopment plan, creating a sense of cultural identity and community pride while improving local amenities [25, 33].
2. **Perrier Mines, France:** A significant JCI was recorded as the transformation of volcanic stone tunnels into underground housing created jobs in construction, tourism, and environmental management [21, 30-36].
3. **Rochefort, Belgium:** A low HAR indicated affordable housing options provided by UHDs, ensuring accessibility for local populations and attracting new residents [16, 29-34].

Redevelopment initiatives can prioritize local communities' welfare by concentrating on socioeconomic indicators, promoting social justice and long-term economic vitality.

5.3. Urban Attractiveness Metrics

Urban attractiveness metrics evaluate the desirability of redeveloped mining regions for residents, businesses, and visitors [4-7, 9-12, 26]. These metrics focus on optimizing urban density, enhancing aesthetic and cultural appeal, and ensuring functional integration of public spaces and amenities (Table 9).

Table 7. Environmental Metrics, Purpose and Interpretation

Metric	Description	Purpose	Interpretation	Parameters	References
Land Utilization Index (LUI)	Measures the proportion of degraded or abandoned land successfully repurposed for sustainable uses, including residential, recreational, or ecological functions.	Tracks the efficiency of land reclamation and redevelopment, minimizing urban sprawl and preserving natural ecosystems.	A higher LUI value indicates that significant portions of degraded land have been effectively utilized for benefits. Lower values highlight underutilization, contamination issues, or barriers to redevelopment.	Percentage of reclaimed land, land use type distribution, redevelopment success rate	[3, 9-15, 38, 51-55]
Thermal Efficiency Score (TES)	Evaluates the energy efficiency of housing developments, mainly underground housing, focusing on their ability to reduce reliance on heating and cooling systems.	Assesses the environmental benefits of utilizing natural insulation provided by subterranean spaces, contributing to energy savings.	A higher TES value reflects efficient thermal performance and reduced dependence on artificial energy sources, while lower values suggest inefficiencies in housing design or high energy consumption.	Heating and cooling demand, energy consumption per square meter, insulation efficiency	[7, 11-19, 21-27, 33-38]
Soil and Groundwater Quality Index (SGQI)	Measures the effectiveness of remediation efforts in improving soil and water quality, ensuring that post-mining areas are safe for human habitation and ecological use.	Evaluates the success of environmental restoration in addressing contamination and promoting sustainable redevelopment.	A higher SGQI value indicates substantial soil and groundwater quality improvements, reducing health and ecological risks. Lower values highlight areas requiring further remediation and environmental management.	Contaminant levels in soil and water, pH balance, heavy metal concentration, ecological toxicity reduction	[1, 14-16, 51-55]

Table 8. Socio-Economic Metrics, Purpose and Interpretation

Metric	Description	Purpose	Interpretation	Parameters	References
Housing Affordability Ratio (HAR)	Assesses housing affordability in redevelopment areas by comparing median housing costs (rent or mortgage) to household income.	Ensures that redevelopment projects provide accessible and affordable housing for diverse income groups, including low-income residents.	A lower HAR value indicates that housing is more affordable, reducing financial strain on residents. Higher values suggest affordability challenges, signaling the need for interventions to lower housing costs.	Median housing cost-to-income ratio, percentage of income spent on housing	[7-16, 29-34]
Job Creation Index (JCI)	Measures the number of jobs generated during and after redevelopment, including opportunities in construction, maintenance, tourism, and local businesses.	Tracks economic revitalization, evaluating the capacity of redevelopment projects to stimulate employment and economic activity.	A higher JCI value reflects successful job creation, fostering economic stability and growth in mining regions. Lower values indicate limited economic impact, requiring additional investments in job-generating activities.	Employment rate change, number of new businesses, workforce participation rate	[18-21, 30-36]
Community Satisfaction Index (CSI)	Gauges residents' satisfaction with redevelopment outcomes, including housing quality, public spaces, amenities, and overall quality of life.	Provides insights into the social inclusivity and acceptance of redevelopment projects, ensuring alignment with community needs.	A higher CSI value indicates positive community perceptions and support for redevelopment. Lower values highlight dissatisfaction, requiring improvements in project planning and implementation.	Resident satisfaction surveys, quality of life indicators, public space usage rates	[15-25, 33, 38]

Table 9. Urban Attractiveness Metrics, Purpose and Interpretation

Metric	Description	Purpose	Interpretation	Parameters	References
Urban Density Adjustment Index (UDAI)	Measures the balance between population density and land use, ensuring efficient space utilization without causing overcrowding or underutilization.	Prevents issues related to overcrowding while promoting vibrant and sustainable urban environments.	A UDAI value 100 indicates a well-balanced density, supporting livability and economic activity. Values too high or too low suggest land use or infrastructure planning inefficiencies.	Population per square kilometer, housing-to-land ratio, infrastructure capacity utilization	[1-3, 7, 9, 20-23]
Aesthetic Value Score (AVS)	Evaluates the visual appeal of urban spaces, including architectural quality, landscaping, and integration with natural surroundings.	Enhances livability and promotes the region as a desirable location for residents and tourists.	Higher AVS values reflect visually appealing, well-designed spaces. Lower values suggest a need for better design and aesthetic improvements.	Public perception surveys, architectural ratings, green space coverage, cultural asset preservation	[11-27, 51-55]
Cultural Integration Index (CII)	Assesses incorporating local cultural heritage, traditions, and community values into redevelopment projects.	Promotes cultural pride, social cohesion, and a sense of place for residents.	A higher CII value indicates successful cultural integration, ensuring redevelopment aligns with community identity and values. Lower values highlight neglect of cultural aspects, potentially leading to social resistance.	Number of cultural elements incorporated, community engagement rates, cultural event participation	[1-9, 22-31, 55]

Applications in Practice

1. **Perrier Mines, France:** A high AVS was achieved by blending modern underground housing designs with preserved natural landscapes, enhancing the region's aesthetic appeal and environmental harmony [27, 51-55].

1. **Rochefort, Belgium:** A high CII reflected the successful integration of mining heritage and local culture into public spaces and housing developments, promoting community pride and tourism [22-31].

3. **South Wales, UK:** The Taff Trail redevelopment project achieved a high UDAI by transforming abandoned mining areas into well-connected recreational and tourism corridors [20-23].

Urban attractiveness metrics ensure that redevelopment projects create vibrant, inclusive, and visually appealing environments, contributing to the long-term success of mining region transformations [20-23]. Using these extensive indexing metrics, stakeholders can assess the impact and progress of redevelopment projects by assessing the environmental, socioeconomic, and urban aspects. These indicators provide a strong foundation for attaining inclusive and sustainable change, guaranteeing that mining areas develop resilient, appealing, and livable urban areas.

6. Case Studies

Urban regeneration has unique potential and challenges as mining areas change [1]. Following the cessation of industrial operations, mining regions frequently experience social disintegration, economic hardship, and environmental damage. However, these places also present significant opportunities for revitalization through innovative planning, such as the creation of underground homes and the reuse of urban voids. This section presents case studies worldwide where creative strategies have been effectively applied to revitalize mining areas, mainly through subterranean dwellings and urban void rehabilitation (refer to Table 10). While these case studies illustrate successful transformations, it is crucial to acknowledge that various contextual factors, including governance structures, socioeconomic conditions, financial resources, and environmental constraints, influence their success. Some strategies may not be directly replicable in other regions due to differences in regulatory frameworks, cultural perceptions of underground housing, or the availability of funding for large-scale redevelopment. Additionally, long-term sustainability challenges such as maintenance costs, social acceptance, and environmental resilience, must be considered when evaluating these projects.

Table 10. Case Studies of Urban Void Redevelopment with Underground Housing (Source: Authors' compilation).

Perrier Mines	Bingham Canyon Mine	Freiberg	Rochefort	Eisenhüttenstadt	**Case Study**
France	USA	Germany	Belgium	Germany	**Location**
Volcanic stone extraction leaves behind extensive underground tunnels.	One of the largest open-pit copper mines facing significant environmental degradation post-mining.	Historical mining town experiencing post-industrial decline. Focus on preserving mining heritage while redeveloping the city.	Decline of coal mining industry, resulting in urban voids and economic challenges.	Former industrial hub, steel production city facing deindustrialization and large urban voids post-reunification.	**Transformation Focus**
Repurposed underground tunnels into housing units as part of urban regeneration. Focused on energy-efficient living, preserving the natural landscape, and transforming the surface area into parks and community spaces.	Utilized mining voids for underground housing, minimizing surface land use. Repurposed the surface area for parks and green spaces while incorporating energy-efficient housing and sustainable infrastructure.	Created the " Mining and Geotechnical Heritage" district, integrating underground housing with cultural tourism and historic preservation. Designed underground units with geothermal heating for energy efficiency.	Repurposing mining voids into multifunctional spaces, including underground housing and public parks. Utilized existing mine shafts for energy-efficient underground living while preserving surface land for green spaces.	Repurposed industrial zones into mixed-use areas, incorporating green spaces, affordable housing, and cultural facilities. Promoted energy-efficient housing and sustainable urban design, blending industrial heritage with modern urban living.	**Key Strategies and Benefits**
Volcanic extraction tunnels	Open-pit mine voids	Former mining sites, cultural heritage	Mining voids, abandoned pits	Industrial voids, large empty sites	**Type of Urban Void Utilized**
Underground housing, public spaces, parks	Energy-efficient underground housing, green infrastructure	Underground homes with geothermal heating and modern amenities	Underground housing units, green spaces, public parks	Energy-efficient housing with modern urban design	**Housing Features**
Preservation of natural landscape, reduced land usage	Land reclamation, improved air, and water quality	Energy-efficient homes, reduced surface land impact	Preserved surface land, reduced environmental degradation	Reduced carbon emissions, energy-efficient development	**Environmental Impact**
Community-focused design, improved quality of life	Improved community engagement through public green spaces	Strengthened community engagement through tourism and heritage	Strengthened community ties, promoted social inclusivity	Improved social cohesion, enhanced quality of life for residents	**Social Impact**
Increased local employment, tourism-driven economic growth	Attracting new businesses and residents, job creation	Increased tourism revenue, cultural tourism integration	Local business growth, tourism, and cultural attraction	Economic revitalization through mixed-use developments	**Economic Impact**
Limited scalability of underground housing beyond specific geological conditions	High costs of environmental remediation and infrastructure adaptation	Dependence on heritage tourism, requiring adaptation to changing visitor trends	Potential resistance to underground housing due to cultural perceptions need for continued government	High maintenance costs and the need for continuous investment in infrastructure upkeep	**Long-Term Challenges**

The salient features of the case studies mentioned above are contrasted in Table 11. This comparative analysis helps uncover similar strategies and challenges encountered while transforming mining districts by utilizing underground dwellings and urban voids to enhance urban attractiveness (refer to Table 11). While these case studies illustrate successful transformations, their outcomes are shaped by various factors, including governance structures, socio-economic conditions, financial resources, and environmental constraints. Additionally, comparing environmental benefits, such as carbon footprint reduction and improved air and water quality, versus economic costs, including infrastructure investments and long-term maintenance, is necessary to understand their feasibility. Furthermore, an assessment of whether these projects yielded long-term economic gains through increased tourism, real estate value, or job creation is critical. In regions like Eisenhüttenstadt and Rochefort, investments in mixed-use developments and tourism-related initiatives have contributed to economic revitalization. However, high initial costs and maintenance expenses present significant financial challenges that must be addressed through innovative funding models and government incentives. Future research should incorporate comparative financial analyses and environmental trade-offs to understand better the economic and ecological sustainability of urban void redevelopment and underground housing projects. Empirical validation through case-specific cost-benefit assessments and stakeholder engagement studies will guide large-scale implementation efforts.

Table 11. Comparative Analysis of Mining Region Transformations (Source: Authors' compilation)

Feature	Eisenhüttenstadt (Germany)	Rochefort (Belgium)	Freiberg (Germany)	Bingham Canyon Mine (USA)	Perrier Mines (France)
Industry Base	Steel production	Coal mining	Coal and silver mining	Copper mining (open-pit)	Volcanic stone extraction
Post-Closure Strategy	Mixed-use redevelopment, green spaces	Underground housing, parks	Mining heritage preservation, underground housing	Underground housing, green space development	Underground housing, surface redevelopment
Urban Voids Repurposed	Industrial zones to mixed-use areas	Mining voids to public amenities and housing	Historical mining structures integrated into urban spaces	Large mining voids converted to underground housing	Mine tunnels converted into residential spaces
Sustainability Initiatives	Energy-efficient buildings, renewable energy	Geothermal energy, underground living	Geothermal heating, sustainable living	Energy-efficient underground housing	Energy-efficient underground housing, parks
Cultural/ Heritage Integration	Preserved industrial heritage	Preservation of mining heritage	Mining Heritage District, tourism	None Specified	None Specified
Urban Attractiveness Improvements	Affordable housing, parks, cultural spaces	Green spaces, community-friendly design	Residential areas, cultural tourism, energy-efficient housing	Energy-efficient living, green spaces	Sustainable living preserved natural landscape
Long-Term Challenges	High maintenance costs, infrastructure upkeep	Cultural resistance, need for government support, funding difficulties delaying redevelopment	Dependence on heritage tourism, visitor fluctuation, policy barriers restricting adaptive reuse	High remediation and adaptation costs	Limited scalability beyond specific geological conditions, technical difficulties in long-term tunnel stability
Funding Difficulties	Limited public-private partnerships for infrastructure financing	Delays in securing investment for large-scale projects	Limited financial incentives for private sector involvement	High cost of environmental remediation impeding investment	High costs of adapting tunnels for habitation and utilities
Policy Barriers	Complex approval processes for redevelopment projects	Restrictive zoning laws and land-use regulations	Bureaucratic delays in approving redevelopment projects	Regulatory challenges related to large-scale land repurposing	Lack of national policies supporting underground housing
Technical Limitations	Retrofitting industrial buildings for housing required extensive structural reinforcement.	Difficulty in reinforcing old mine shafts for long-term habitation	Ground stability concerns due to aging mining infrastructure	Engineering difficulties in stabilizing large pit voids for housing	Challenges in maintaining long-term structural stability in tunnels

The case studies demonstrate several common themes in improving urban attractiveness in mining regions through the repurposing of urban voids and the incorporation of underground housing:

1. **Sustainable and Energy-Efficient Housing:** Many case studies emphasized energy-efficient living through underground housing. The natural temperature stability of underground spaces contributed to reducing energy consumption, particularly heating and cooling. In some cases, geothermal systems were used to reduce energy usage further, making these developments more attractive to environmentally conscious residents. Additionally, these initiatives contributed to carbon footprint reduction by

decreasing reliance on conventional energy sources. However, long-term maintenance and cost-effectiveness remain concerns, as initial infrastructure investments for underground developments can be high, requiring significant financial planning and continued operational costs [9-11, 23-30, 33-37].

2. **Land Preservation and Green Space Integration:** For parks, green areas, and community facilities, these designs were able to maintain surface-level land by using subterranean spaces. In addition to making the region more aesthetically pleasing, this also increased the standard of living for locals. However, environmental remediation efforts and land stabilization costs vary significantly across sites. In some cases, the economic costs of land reclamation were offset by increased real estate values and tourism revenue generated by the newly established green spaces [20-27, 30-38]. In regions like Rochefort and Bingham Canyon, transforming industrial sites into green spaces helped mitigate the negative impacts of urban voids and created inviting environments for new residents while boosting local economies.

3. **Cultural and Social Revitalization:** Preserving the cultural heritage of these mining regions played a key role in enhancing their attractiveness. In Freiberg, for example, integrating mining heritage into the redevelopment plan created a sense of identity and pride among residents. However, in regions where cultural identity is less defined by mining history, achieving social acceptance for underground housing may require additional public engagement and incentives. Furthermore, some projects that successfully incorporated cultural heritage elements also saw increased tourism revenue, with repurposed sites becoming historical attractions that added economic value to the region [20-22].

4. **Economic Revitalization and Job Creation:** Renewing mining regions through urban void redevelopment and underground housing initiatives led to job creation and economic revitalization. The construction phase generated employment, while the long-term benefits included attracting new businesses and residents and contributing to local economic growth. However, continued investment in infrastructure and economic diversification is necessary to sustain growth beyond the initial redevelopment phase. In some cases, tourism-based revenues and rising property values have reinforced the long-term financial benefits of these projects. In contrast, in others, the dependence on government subsidies and private sector investments remains a key challenge [7, 22, 38]. This economic boost was particularly evident in cities like Eisenhüttenstadt and Rochefort, where urban transformation attracted investment and new development.

The case studies from Perrier Mines, Bingham Canyon, Rochefort, Eisenhüttenstadt, and Freiberg demonstrate how underground housing and urban void rehabilitation can significantly impact post-mining areas. Urban attractiveness is enhanced by these measures, which promote sustainability, preserve cultural heritage, provide green spaces, and make cities more habitable. These places have demonstrated how urban voids may be used to build vibrant, sustainable communities by combining innovative housing ideas with the unique characteristics of mining settings. However, the long-term success of these projects is contingent on adaptable strategies that account for socio-economic conditions, environmental constraints, and financial viability. Future research should further investigate the replicability of these models in varying global contexts, focusing on empirical validation, stakeholder engagement, and comparative economic and environmental impact assessments to determine their true long-term sustainability.

6.1. Application of Indexing Metrics to Case Studies

This section applies key indexing metrics to selected case studies to bridge the gap between theoretical frameworks and practical applications. The Land Utilization Index (LUI) and Thermal Efficiency Score (TES) are utilized to assess the impact of redevelopment efforts in Rochefort and Freiberg, respectively. These assessments provide a tangible understanding of how these metrics can guide post-mining redevelopment efforts.

6.1.1. Land Utilization Index (LUI) in Rochefort

Rochefort's transformation from an abandoned coal mining region into a mixed-use development integrating underground housing and green spaces presents an opportunity to evaluate improvements in land efficiency. The LUI is calculated as follows:

$$LUI = \frac{Redeveloped\ land\ Area}{Total\ Available\ Land\ Area} \times 100 \qquad (1)$$

Before redevelopment, only 30% of Rochefort’s post-mining land was actively utilized. Following redevelopment, approximately 75% of the available land was repurposed for housing, public parks, and community spaces. Applying the LUI formula:

$$LUI_{before} = \frac{30}{100} \times 100 = 30\%$$
$$LUI_{after} = \frac{75}{100} \times 100 = 75\% \quad (2)$$

This substantial improvement demonstrates the effectiveness of land repurposing strategies in enhancing urban attractiveness and optimizing land use in post-mining regions.

6.1.2. Thermal Efficiency Score (TES) in Freiberg

Freiberg's underground housing initiatives leverage the insulating properties of subsurface spaces to enhance energy efficiency. The TES is determined based on reductions in heating and cooling energy demand compared to conventional surface housing. The formula used is:

$$TES = \frac{Standard\ Energy\ Demand - Underground\ Housing\ Energy\ Demand}{Standard\ Energy\ Demand} \times 100 \quad (3)$$

Data from similar underground projects indicate that traditional housing in Freiberg requires approximately 150 kWh/m² annually for heating and cooling, whereas underground housing reduces this to 90 kWh/m². Applying the TES formula:

$$TES = \frac{150 - 90}{150} \times 100 = 40\% \quad (4)$$

This calculation suggests a 40% improvement in thermal efficiency, reinforcing the sustainability advantages of UHSs.

These calculations illustrate how indexing metrics can be effectively applied to evaluate and guide redevelopment projects in post-mining landscapes. The LUI confirms the efficient repurposing of former mining sites, while the TES highlights the environmental benefits of underground housing. Future empirical research should further validate these findings through site-specific data collection and expanded case studies to ensure these indexing measures are adaptable across different post-mining contexts.

7. Discussion

A comprehensive evaluation of mining region redevelopment requires the application of structured frameworks to assess their long-term viability. This discussion examines the redevelopment of five key mining regions—Eisenhüttenstadt, Rochefort, Freiberg, Bingham Canyon Mine, and Perrier Mines—to highlight how the proposed indexing metrics, such as the LUI and the TES, have influenced redevelopment decision-making and contributed to sustainable outcomes. However, while these redevelopment efforts have demonstrated positive transformations, several technical, financial, and regulatory challenges must be critically examined to assess the feasibility and scalability of similar projects elsewhere.

Eisenhüttenstadt, Germany, originally developed as a planned steel production city, faced significant challenges following industrial decline. Redevelopment efforts successfully transformed large industrial voids into mixed-use areas, incorporating green spaces and modern housing. Integrating cultural heritage with urban renewal improved social cohesion and economic stability. Applying the Land Utilization Index provided a precise measure of land repurposing efficiency, demonstrating an increase in land optimization and offering insights into the economic and spatial benefits of the redevelopment. Despite these successes, construction feasibility remained a key challenge, as repurposing industrial infrastructure required extensive structural modifications and adherence to strict regulatory standards for building safety and environmental compliance. In Rochefort, Belgium, the decline of coal mining left extensive urban voids, which were successfully repurposed into underground housing and public parks. Before redevelopment, only 30% of post-mining land was actively used, whereas following structured interventions, approximately 75% was optimized for residential and recreational purposes. Analyzing the LUI before and after redevelopment illustrated significant improvements in urban land use. The structured planning strategies ensured that land conversion efforts contributed to urban attractiveness and economic revitalization, mainly through sustainable housing and tourism-related activities. However, long-term structural stability remains an ongoing concern. Many former mining regions experience subsidence, which poses a risk to underground developments. The presence of abandoned mine shafts increases the likelihood of ground instability, necessitating constant monitoring and reinforcement strategies to ensure the safety and longevity of UHSs. Freiberg, Germany, provides another example of successful redevelopment: underground housing was integrated into urban planning while preserving the city's mining heritage. The city improved residential areas' energy efficiency by utilizing underground spaces. In this instance, applying the TES illustrates the advantages of subterranean housing in lowering energy usage. Data indicate that conventional housing in Freiberg required approximately 150 kWh/m² annually for heating and cooling, whereas underground housing reduced this demand to 90 kWh/m². The TES calculation confirmed a 40% improvement in thermal efficiency, reinforcing the sustainability advantages of UHSs. However, water infiltration presents a significant challenge in underground housing projects, particularly in regions with high groundwater levels. Ensuring long-term durability requires sophisticated drainage systems and waterproofing technologies, which can add to the overall cost of implementation and maintenance. Bingham Canyon Mine in the United States, one of the world's largest open-pit copper mines, faced substantial environmental degradation following the cessation of operations. Unlike Eisenhüttenstadt and Rochefort, redevelopment in Bingham Canyon has not yet been systematically integrated with urban repurposing strategies. The absence of structured frameworks has resulted in limited land reutilization, with large sections of the mining voids remaining underutilized. One of the primary barriers to redevelopment is financial viability. Large-scale redevelopment of an open-pit mine requires significant upfront investment, and uncertainties regarding economic returns have deterred private investment. Additionally, stringent environmental regulations necessitate costly remediation measures before redevelopment can commence, further complicating financial planning and execution. Perrier Mines in France offers another unique case where former volcanic stone extraction tunnels have been transformed into underground housing and recreational spaces. This approach capitalized on existing geological formations to create sustainable living environments. However, a lack of comprehensive cost-benefit analysis limits the ability to assess this approach's long-term financial and ecological viability fully. While the geological conditions of volcanic rock provide inherent stability, long-term monitoring is necessary to address potential structural degradation over time. Furthermore, the financial sustainability of such projects remains uncertain, as initial construction and adaptation costs for underground living spaces are significantly higher than conventional above-ground housing. The long-term economic viability of underground developments depends on the availability of incentives, market demand, and the willingness of governments and private investors to support such initiatives.

The comparison of these case studies underscores the importance of structured redevelopment frameworks in mining regions. In cities like Rochefort and Freiberg, where structured planning strategies have been implemented, there are clear benefits in land utilization and energy efficiency. Conversely, the lack of structured redevelopment metrics has continued land underutilization in areas like Bingham Canyon Mine. However, beyond the benefits of redevelopment, the discussion highlights the critical challenges that must be addressed, including construction feasibility, long-term structural stability, and financial viability. Decision-makers have been able to quantitatively evaluate the success of redevelopment initiatives by methodically using indexing frameworks like LUI and TES, guaranteeing a well-rounded strategy that considers social inclusion, economic viability, and environmental sustainability. Future research should focus on empirical studies that validate these frameworks through field applications, case-specific evaluations, and long-term economic analyses to optimize redevelopment strategies for post-mining landscapes while mitigating associated risks.

7.1. Challenges and Limitations

Redeveloping mining regions is a complex process involving socio-economic, environmental, and regulatory challenges. These challenges stem from the long-term impacts of mining activities and the constraints of transforming degraded landscapes into sustainable urban spaces. Addressing these issues requires innovative strategies and collaborative approaches (Table 12).

Socio-economic constraints include job losses, gentrification, and inadequate infrastructure in post-mining regions. These issues hinder redevelopment by reducing community engagement and economic viability. Regions like Freiberg, Germany, successfully mitigated these challenges through community-centered redevelopment and heritage tourism, creating jobs and preserving cultural identity. Environmental challenges arise from contaminated soil, polluted water, and unstable land. These issues necessitate extensive remediation efforts to ensure the safety and sustainability of redevelopment projects. The Ruhr Valley, Germany, is a successful example of integrating ecological restoration with urban renewal, creating green spaces and boosting biodiversity. Regulatory and governance challenges often include unclear policies, bureaucratic delays, and land ownership conflicts. These barriers slow down redevelopment and discourage investments. Rochefort, Belgium, addressed such issues by introducing tailored zoning laws and creating incentives for innovative solutions like underground housing.

Table 12, Challenges, Implications, and Solutions for Sustainable Redevelopment of Post-Mining Regions

Category	Definition	Challenges	Implications	Proposed Solutions
Socio-Economic Constraints	Issues related to redevelopment's economic and social aspects, including job creation, housing affordability, and infrastructure.	**Economic Dislocation:** Closure of mines leads to job losses and economic stagnation.	Reduced local spending, outmigration, and diminished economic viability.	Foster skill development programs, incentivize diverse industries and support small businesses.
		Community Resistance: Distrust of projects perceived as benefiting outsiders.	Social tensions and delays in implementation.	Engage communities through participatory planning, transparent communication, and equitable benefit sharing.
		Limited Infrastructure: Inadequate education, healthcare, and transportation facilities.	Hinders workforce development and deters investors.	Invest in basic infrastructure, integrate education programs, and ensure access to essential services.
		Housing Affordability: Rising property values displace low-income residents.	Gentrification and loss of social equity.	Implement affordable housing policies, rent control measures, and provide subsidies for vulnerable groups.
Environmental Remediation Needs	Challenges associated with restoring ecological health and mitigating environmental damage from mining activities.	**Soil and Water Contamination:** Toxic substances degrade land and water resources.	Health risks for residents, limited land usability for agriculture or housing.	Use bioremediation, soil washing, and advanced water treatment systems for effective remediation.
		Land Instability: Unstable terrain and sinkholes from abandoned mines.	Safety hazards for infrastructure and housing developments.	Conduct geotechnical surveys, stabilize subsurface structures, and adopt engineering safeguards.
		Biodiversity Loss: Habitat destruction reduces ecological resilience.	Decreased environmental quality and loss of ecosystem services.	Reintroduce native vegetation, create green infrastructure, and establish ecological corridors.
		High Remediation Costs: Restoration efforts are expensive and resource-intensive.	Financial constraints delay or limit redevelopment projects.	Develop public-private partnerships, access green financing, and secure government grants for restoration.
Regulatory and Governance Issues	Barriers related to policy frameworks, stakeholder coordination, and public acceptance of	**Absence of Legal Frameworks:** Lack of guidelines for underground housing and land reuse.	Uncertainty for developers, delays in project approvals.	Create clear regulations tailored to subterranean development and sustainable land use.
		Bureaucratic Inefficiencies: Lengthy and complex permitting processes.	Increased project costs, reduced investor confidence.	Streamline regulatory processes through one-stop approval mechanisms.
		Land Ownership Disputes: Conflicts over land rights among stakeholders.	Delays in project initiation and coordination challenges.	Resolve disputes with clear land policies and stakeholder agreements.
		Public Perception of Safety: Concerns about safety of underground housing and land reuse.	Resistance from communities reduced project acceptance.	Educate the public, conduct safety audits, and implement robust construction standards.

These challenges highlight the complexities of transforming post-mining landscapes into sustainable and livable environments. Socio-economic constraints require inclusive planning and investment to uplift local communities. Environmental remediation necessitates advanced techniques to restore land and ecosystems. Regulatory and governance barriers require clear frameworks and streamlined processes to ensure timely and effective implementation. Mining region redevelopment requires a multidimensional approach to overcome socio-economic, environmental, and regulatory challenges. Mining landscapes can be converted into resilient, inclusive, and sustainable urban settings by implementing creative solutions and encouraging stakeholder cooperation.

7.2. Guidelines for Sustainable Redevelopment

Sustainable redevelopment of mining regions demands a holistic approach that integrates environmental restoration, social inclusivity, economic viability, and effective governance. Addressing these dimensions ensures that transformation efforts are resilient, equitable, and aligned with long-term sustainability goals. Environmental remediation is fundamental to creating a safe and habitable environment in post-mining landscapes. Priority should be given to soil and water remediation using advanced techniques such as bioremediation, soil washing, and groundwater treatment to eliminate contaminants. Continuous monitoring of environmental conditions is essential to ensure the restored land is suitable for redevelopment. Reintroducing native vegetation through ecological restoration programs can enhance biodiversity, create green corridors, and contribute to urban greening initiatives. Developing green infrastructure, including parks, wetlands, and renewable energy systems like solar farms or geothermal heating, restores ecological balance, improves urban attractiveness, and supports clean energy adoption. Social inclusivity is critical to ensuring that redevelopment efforts equitably benefit all stakeholders. Community engagement should be central to the planning process, with participatory workshops and consultations to include local voices and align projects with their cultural, social, and economic needs. Housing policies must prioritize affordability to prevent gentrification and displacement. Developers should be incentivized to build energy-efficient homes accessible to low- and middle-income populations. Investments in social infrastructure such as healthcare, education, and transportation are essential to improving quality of life and ensuring inclusivity in public spaces and housing projects. Economic viability is key to the long-term success of redevelopment initiatives. Job creation should be a top priority, focusing on employing local labor for construction, remediation, and other redevelopment activities. Diversifying the economy through industries such as tourism, renewable energy, and small-scale manufacturing can provide sustainable income sources. Public-private partnerships (PPPs) can be crucial in securing investments for large-scale projects, while training programs and grants can support local enterprises and artisans. Developing marketplaces and tourism initiatives can further boost local commerce and attract visitors. Figure 4 outlines the policy framework and implementation strategy for urban void redevelopment and underground housing integration.

Effective governance and supportive policy frameworks are vital for overcoming regulatory barriers and ensuring successful project implementation. Simplifying permitting and licensing processes through one-stop approval mechanisms can reduce bureaucratic inefficiencies. Clear and specific guidelines for underground housing and urban void reuse are necessary to provide direction and confidence to developers. Transparency and accountability should be prioritized through robust monitoring systems and regular stakeholder updates. Collaboration among governments, private developers, environmental experts, and local communities is essential to align efforts with national and regional sustainability agendas and secure funding and policy support. These suggestions (refer to Figure 4) can be incorporated into redevelopment plans to turn mining areas into thriving, diverse, and resilient urban areas. This all-encompassing strategy addresses environmental, social, and economic issues to build a sustainable future for present and future generations while guaranteeing that the advantages of redevelopment are shared fairly.

7.3. Practical Application for Different Stakeholders

The successful implementation of urban void redevelopment and underground housing strategies relies on the active participation of multiple stakeholders, each contributing to sustainable and resilient post-mining landscapes. Government authorities are crucial in developing regulatory frameworks and zoning policies to facilitate land reclamation and underground housing integration. They also provide financial incentives such as tax credits and grants to support sustainable redevelopment projects while ensuring compliance with environmental standards through impact assessments and monitoring programs.

Urban planners and policymakers focus on designing integrated master plans that align underground housing with urban void rehabilitation strategies. They implement sustainability-focused land-use planning to optimize space utilization and minimize environmental degradation while establishing performance metrics, such as the LUI and TES, to evaluate the effectiveness of redevelopment efforts. Private developers and investors collaborate with local governments to invest in pilot projects that demonstrate the feasibility of underground housing. They integrate innovative construction technologies to ensure structural stability and long-term resilience while adopting PPP models to secure funding and optimize cost efficiency. Local communities and advocacy groups actively participate in decision-making to ensure that redevelopment efforts align with community needs and cultural values. They support awareness campaigns to address public perceptions and acceptance of UHSs while monitoring project outcomes to provide feedback and advocate for improvements based on lived experiences. Environmental experts and researchers conduct feasibility studies to assess the ecological impact of underground housing and urban void redevelopment. They develop innovative remediation techniques to address soil contamination, groundwater management, and land stabilization while generating empirical data to refine existing sustainability metrics and policy frameworks. Redevelopment initiatives can attain a balanced strategy that supports social inclusion, economic growth, and environmental preservation in mining areas by including these stakeholder-driven applications.

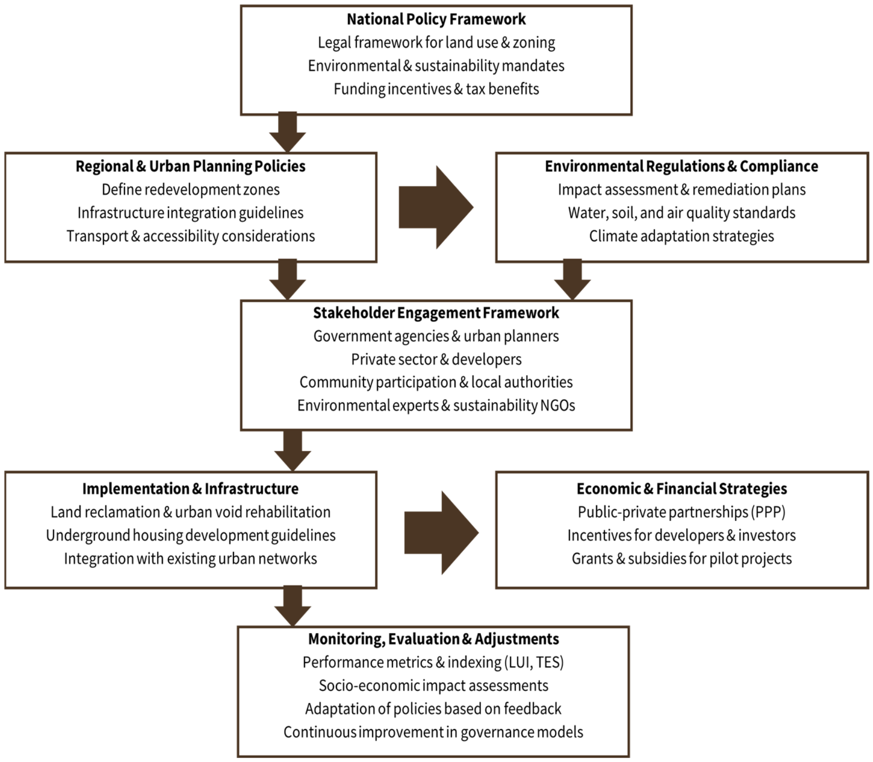

Figure 4. Policy framework and implementation strategy for sustainable urban void redevelopment and underground housing integration (Source: Authors)

8. Conclusions

Redeveloping mining regions presents a unique opportunity to address the environmental challenges of abandoned mining sites, enhance urban attractiveness, and improve the quality of life for local communities. Urban voids, often considered negative spaces left behind by mining activities, possess significant transformative potential. When repurposed thoughtfully, these voids can be converted into green spaces, public amenities, or even residential areas, significantly improving the urban landscape. Similarly, UHSs can overcome land scarcity while preserving valuable surface areas for other uses. Mining areas can be transformed into sustainable, lively, and appealing urban settings by incorporating these cutting-edge strategies.

This work is based on secondary data and conceptual analysis, so its findings provide a theoretical foundation rather than empirical validation. While the research highlights key redevelopment strategies and indexing metrics, further real-world studies are necessary to assess their practical applicability. Future research should focus on empirical validation through stakeholder surveys, pilot projects, and field-based studies that evaluate the socio-economic and environmental impact of integrating urban voids with underground housing. Additionally, there is a need for empirical studies that evaluate long-term economic viability, cost-efficiency, and environmental mitigation measures to ensure that these strategies are both financially feasible and ecologically sustainable. To enhance the applicability of these frameworks, future research should prioritize collecting and analyzing actual site data from redeveloped and underutilized mining regions to provide a comprehensive understanding of how these strategies perform in real-world conditions. Despite the promising potential of these redevelopment strategies, significant challenges and risks must be acknowledged. Construction feasibility remains a critical concern, particularly in UHDs where excavation and reinforcement of subsurface spaces pose engineering complexities. Issues such as soil stability, subsidence risks, and structural reinforcement require advanced geotechnical assessments to ensure long-term viability. Water infiltration and material durability must also be addressed to prevent long-term structural degradation. Financial viability presents another substantial hurdle, as underground housing and large-scale land rehabilitation projects require high initial investment costs. Ongoing maintenance expenses and uncertainties regarding economic returns further complicate project feasibility. Innovative financing models, public-private partnerships, and government incentives will be necessary to sustain long-term redevelopment efforts. Regulatory constraints also pose significant barriers, as zoning laws, land-use policies, and environmental compliance requirements vary across jurisdictions. Overcoming these legal and administrative hurdles will require coordinated efforts between urban planners, policymakers, and industry stakeholders.

The case studies analyzed in this study illustrate the successes and challenges of mining region redevelopment. While Rochefort and Freiberg exemplify successful transformations, they highlight key obstacles such as funding, policy, and technical limitations. In Rochefort, delays in securing investment and regulatory constraints on underground housing development created significant hurdles. Freiberg's redevelopment faced challenges related to heritage tourism dependence and the need for specialized geotechnical expertise to ensure structural stability. Similarly, Perrier Mines encountered technical limitations in adapting tunnels for long-term residential use, necessitating ongoing structural reinforcements. Addressing these setbacks is crucial for developing adaptable, scalable redevelopment models that can be applied in different mining contexts. Indexing measures are critical in assessing how well redevelopment initiatives are working. These measures function as quantifiable markers of achievement in several areas, including urban attractiveness, socioeconomic impact, and environmental sustainability. Policymakers and developers can evaluate the status of redevelopment projects, pinpoint areas for improvement, and guarantee that sustainability objectives are fulfilled by employing particular metrics like the LUI, HAR, and UDAI. These metrics provide a robust framework for guiding redevelopment efforts, ensuring that they align with both short-term needs and long-term goals. However, to fully operationalize these frameworks, it is necessary to move beyond theoretical application and implement these metrics in active redevelopment projects. Collaborations with urban planners, policymakers, and mining companies will be instrumental in testing and refining these metrics, ensuring they are adaptable across different mining contexts and development models.

The findings from this paper point to the significant potential of integrating urban voids and underground housing in mining regions. However, several challenges remain, particularly regarding socio-economic acceptance, environmental remediation, and regulatory frameworks. Future empirical research should aim to validate these concepts through in-depth field studies, including assessments of community perceptions, technical feasibility, and long-term sustainability of redevelopment efforts. Future studies should also focus on feasibility concerns, cost-benefit trade-offs, and long-term performance evaluations to ensure that redevelopment strategies remain viable over extended periods. For implementation, redevelopment projects must prioritize a multi-stakeholder approach that involves local communities, government authorities, private developers, and environmental experts. Strong governance, inclusive planning, and targeted policies will be key to overcoming the challenges associated with these projects. Additionally, exploring innovative financing models and incentives for developers and local authorities can help make these transformative projects more feasible and attractive. Integrating urban voids and underground housing in mining regions holds immense potential for sustainable urban redevelopment. Mining regions can be made resilient, livable, and appealing to future generations by applying the suggested conceptual framework, following established indexing measures, and pursuing further research to test, refine, and implement these strategies in real-world contexts. Establishing direct partnerships with industry stakeholders and regulatory bodies will be crucial in transforming these conceptual frameworks into practical tools for guiding mining region redevelopment at a global scale.

References

[1]. Hajkazemiha, N., Shariat, M., Monavari, M., & Ataei, M. (2021). Evaluation of mine reclamation criteria

using Delphi-Fuzzy approach. *Journal of Mining and Environment, 12*(2), 367-384.

[2]. Winde, F. (2020). Turning water pollution sources into assets: Exploring innovative options of using abandoned mines for generating and storing renewable energy. *Geography, environment, sustainability*, *13*(2), 6-16.

[3]. Pareek, S., & Kumar, M. (2024). Factors affecting land value of urban voids in western part of India. *Journal of Engineering and Applied Science*, *71*(1), 44.

[4]. Pluta, A. (2017). Urban void as a potential of the contemporary city development. *Biblioteka regionalisty*, (17), 95-103.

[5]. Hashem, O. M., Wahba, S. M. E., & Nasr-Eldin, T. I. (2022). Urban voids: Identifying and optimizing urban voids potential as a revitalization source in enhancing developing countries' city income. *Journal of Engineering and Applied Science*, *69*, 1-30.

[6]. Aleha, A., Zahra, S. M., Qureshi, S., Marri, S. A., Siddique, S., & Hussain, S. S. (2023). Urban void as an urban catalyst bridging the gap between the community. *Frontiers in Built Environment*, *9*, 1068897.

[7]. Romão, J., Kourtit, K., Neuts, B., & Nijkamp, P. (2018). The smart city as a common place for tourists and residents: A structural analysis of the determinants of urban attractiveness. *Cities*, *78*, 67-75.

[8]. Kourtit, K., Nijkamp, P., & Wahlström, M. H. (2021). How to make cities the home of people–a 'soul and body'analysis of urban attractiveness. *Land use policy*, *111*, 104734.

[9]. Devrath, A. S. C. (2016). Potential of Earth Sheltered Buildings for Thermalcomfort. *International Journal of Advanced Research and Review (IJARR)*, *1*(10), 88-98.

[10]. Mahdi, R. M., & Aboud, A. H. (2021, February). Underground housing formation strategies. In *Journal of Physics: Conference Series, 1773*(1), 012033). IOP Publishing.

[11]. Lembo, F., Marino, F. P. R., & Calcagno, C. (2011). Semi-underground house models as new concepts for urban sustainable environment. *Procedia Engineering*, *21*, 570-579.

[12]. Cho, I. S., Heng, C. K., & Trivic, Z. (2015). *Re-framing urban space: urban design for emerging hybrid and high-density conditions*. Routledge.

[13]. Nag, A., & Mishra, S. (2024). Sustainable competitive advantage in heritage tourism: Leveraging cultural legacy in a data-driven world. In *Review of Technologies and Disruptive Business Strategies, 3,* 137-162). Emerald Publishing Limited.

[14]. Moirongo, B. O. (2002). Urban public space patterns: human distribution and the design of sustainable city centres with reference to Nairobi CBD. *Urban Design International*, *7*, 205-216.

[15]. AL-Mohannadi, A. S., AL-Mohannadi, M. S., Pokharel, S., Ayari, M. A., & Furlan, R. (2023). Mitigation of urban voids in traditional neighborhoods: The case of the Al-Najada zone in Doha, Qatar. *Journal of Urban Management*, *12*(4), 327-343.

[16]. Rogerson, C. M., & Rogerson, J. M. (2021). Urban tourism under apartheid: The Johannesburg chapter. *Urban tourism in the global south: South African perspectives*, 149-172.

[17]. Rodewald, H. (2022). Creative Frontiers: Germany's Ruhr Area as a Space of Polyrational Possibility. *The Complex City: Social and Built Approaches and Methods*, 49-62.

[18]. Couch, C., Sykes, O., & Börstinghaus, W. (2011). Thirty years of urban regeneration in Britain, Germany and France: The importance of context and path dependency. *Progress in planning*, *75*(1), 1-52.

[19]. Keough, S. B. (2015). Planning for growth in a natural resource boomtown: Challenges for urban planners in Fort McMurray, Alberta. *Urban Geography*, *36*(8), 1169-1196.

[20]. Murtagh, R. (2015). Exploring Maboneng as an international urban tourism attraction within Johannesburg.

[21]. Nag, A., & Mishra, S. (2023). Stakeholders' perception and competitiveness of heritage towns: A systematic literature review. *Tourism Management Perspectives*, *48*, 101156.

[22]. Nag, A., & Mishra, S. (2024). Exploring Dark Tourism in Mining Heritage: Competitiveness and Ethical Dilemmas. *Journal of Mining and Environment*, *15*(3), 863-887.

[23]. Bangian, A. H., Ataei, M., Sayadi, A. R., & Gholinegad, A. R. (2011). The application of fuzzy MADM modeling to define optimum post-mining land use for pit area to recognize reclamation costs in open pit mining. *Archives of Mining Science, 56*(1), 91–116.

[24]. Alavi, I., Ebrahimabadi, A., & Hamidian, H. (2022). A new technical and economic approach to optimal plant species selection for open-pit mine reclamation process. *Journal of Mining and Environment, 13*(4), 1091-1105.

[25]. Bangian, A. H., Ataei, M., Sayadi, A. R., & Gholinegad, A. R. (2011). Fuzzy analytical hierarchy processing to define optimum post-mining land use for pit area to clarify reclamation costs. *Mineral Resources Management (Gospodarka Surowcami Mineralnymi), 56*(2), 145-168.

[26]. Evans, D., Stephenson, M., & Shaw, R. (2009). The present and future use of 'land'below ground. *Land Use Policy*, *26*, S302-S316.

[27]. Walliss, J., & Kok, K. (2014). New interpretative strategies for geotourism: an exploration of two Australian mining sites. *Journal of tourism and cultural change*, *12*(1), 33-49.

[28]. Cui, J., & Lin, D. (2016). Utilisation of underground pedestrian systems for urban sustainability. *Tunnelling and Underground Space Technology*, *55*, 194-204.

[29]. Tranzatto, M., Mascarich, F., Bernreiter, L., Godinho, C., Camurri, M., Khattak, S., ... & Alexis, K. (2022). Cerberus: Autonomous legged and aerial robotic exploration in the tunnel and urban circuits of the darpa subterranean challenge. *arXiv preprint arXiv:2201.07067*, 3.

[30]. Menéndez, J., Ordóñez, A., Álvarez, R., & Loredo, J. (2019). Energy from closed mines: Underground energy storage and geothermal applications. *Renewable and Sustainable Energy Reviews*, *108*, 498-512.

[31]. Manaugh, G. (2016). *Global undergrounds: Exploring cities within*. Reaktion Books.

[32]. Beveridge, R., Kip, M., & Oevermann, H. (2022). From wastelands to waiting lands: Retrieving possibility from the voids of Berlin. *City*, *26*(2-3), 281-303.

[33]. Whitbread-Abrutat, P. (2024). A mine ends. Then what? Some reflections on best practice. In *Mine Closure 2024: Proceedings of the 17th International Conference on Mine Closure*, 3-16. Australian Centre for Geomechanics.

[34]. Ruming, K., McGuirk, P., & Mee, K. (2021). What lies beneath? The material agency and politics of the underground in urban regeneration. *Geoforum*, *126*, 159-170.

[35]. Labbé, M. (2016). Architecture of underground spaces: From isolated innovations to connected urbanism. *Tunnelling and Underground Space Technology*, *55*, 153-175.

[36]. Colomb, C. (2012). Pushing the urban frontier: Temporary uses of space, city marketing, and the creative city discourse in 2000s Berlin. *Journal of urban affairs*, *34*(2), 131-152.

[37]. Earney, F. C., & Green, J. E. (1977). Mining, planning, and the urban environment. *Critical Reviews in Environmental Science and Technology*, *7*(1), 1-89.

[38]. Li, H. (2013). *An Integrated Strategy for Sustainable Underground Urbanization,* 5869. EPFL.

[39]. Pouresmaieli, M., Qarahasanlou, A. N., & Ataei, M. (2024). An evolution in sustainable development: Integrating new semi-quantitative assessment model with strategic management (Insights from the mineral sector). *Case Studies in Chemical and Environmental Engineering*, *10*, 100983.

[40]. Salehi, S., Pouresmaieli, M., & Qarahasanlou, A. N. (2025). A sustainable way to prevent oral diseases caused by heavy metals with phytoremediation. *Case Studies in Chemical and Environmental Engineering*, 101106.

[41]. Pouresmaieli, M., Ataei, M., Qarahasanlou, A. N., & Barabadi, A. (2024). Corporate social responsibility in complex systems based on sustainable development. *Resources Policy*, *90*, 104818.

[42]. Pouresmaieli, M., Ataei, M., Nouri Qarahasanlou, A., & Barabadi, A. (2024). Multi-criteria Decision-making Methods for Sustainable Decision-making in the Mining Industry (A Comprehensive Study). *Journal of Mining and Environment*, *15*(2), 683-706.

[43]. Nag, A. (2025). Stakeholders' perception influence in competitive heritage place-making: case study India. *Proceedings of the Institution of Civil Engineers-Urban Design and Planning*, 1-76.

[44]. Pouresmaieli, M., Ataei, M., Qarahasanlou, A. N., & Barabadi, A. (2024). Building ecological literacy in mining communities: A sustainable development perspective. *Case Studies in Chemical and Environmental Engineering*, *9*, 100554.

[45]. Pouresmaieli, M., Ataei, M., & Qarahasanlou, A. N. (2023). A scientometrics view on sustainable development in surface mining: Everything from the beginning. *Resources policy*, *82*, 103410.

[46]. Nag, A. (2024). Local development and tourism competitiveness: Analyzing the economic impact of heritage tourism initiatives. In *Gastronomic Sustainability Solutions for Community and Tourism Resilience*, 160-190. IGI Global.

[47]. Pouresmaieli, M., Ataei, M., Forouzandeh, P., Azizollahi, P., & Mahmoudifard, M. (2022). Recent progress on sustainable phytoremediation of heavy metals from soil. *Journal of Environmental Chemical Engineering*, *10*(5), 108482.

[48]. Pouresmaieli, M., & Osanloo, M. (2019, November). Establishing a model to reduce the risk of premature mine closure. In *IOP Conference Series: Earth and Environmental Science*, *362*(1), 012005. IOP Publishing.

[49]. Nag, A., & Rathore, A. S. (2025). Balancing Bias and Sustainability in Heritage Tourism. In *Destination Branding and Bias in Ecotourism*, 217-266. IGI Global Scientific Publishing.

[50]. Nag, A., & Rathore, A. S. (2024). Digital Innovation and Destination Competitiveness. *Journal of Mining and Environment*.

[51]. Talento, K., Amado, M., & Kullberg, J. C. (2020). Quarries: From abandoned to renewed places. *Land*, *9*(5), 136.

[52]. Dey, S. D., & Singh, R. (2021). Mapping precarious energy geographies: Exploring the lived experience of coal mining in Jharia, India. *Energy Research & Social Science*, *82*, 102298.

[53]. Winde, F., Kaiser, F., & Erasmus, E. (2017). Exploring the use of deep level gold mines in South Africa for underground pumped hydroelectric energy storage schemes. *Renewable and Sustainable Energy Reviews*, *78*, 668-682.

[54]. Francaviglia, R. V. (1997). *Hard places: Reading the landscape of America's historic mining districts*. University of Iowa Press.

[55]. Storm, A. (2014). *Post-industrial landscape scars*. Springer.

دگرگونی مناطق معدنی از طریق توسعه مجدد پایدار با فضاهای خالی شهری و مسکن زیرزمینی

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چکیده:

این مقاله با ادغام فضـاهای خالی شـهری و راه‌حل‌های مسـکن زیرزمینی، اسـتراتژی‌های توسـعه پایدار برای مناطق پس از معدن‌کاری را بررسـی می‌کند. مناظر معدنی، که اغلب با محیط‌های تخریب‌شـده، رکود اجتماعی-اقتصـادی و فضـاهای کم‌اسـتفاده مشـخص می‌شـوند، چالش‌ها و فرصـت‌های قابل توجهی را برای تحول ارائه می‌دهند. فضاهای خالی شهری مانند گودال‌های متروکه، مجتمع‌های صنعتی و سکونتگاه‌های کارگری منسوخ‌شده را می‌توان به زیرساخت‌های سبز، امکانات عمومی یا فضاهای مسکونی تبدیل کرد. مسکن زیرزمینی، با بهره‌گیری از عایق‌بندی طبیعی محیط‌های زیرسطحی، راه‌حل‌های کارآمد از نظر انرژی ارائه می‌دهد، در حالی که زمین‌های سـطحی را برای مصـارف اکولوژیکی و عمومی حفظ می‌کند. این تحقیق یک چارچوب مفهومی ارائه می‌دهد که اسـتفاده مجدد تطبیقی از فضـاهای خالی شـهری را با طرح‌های نوآورانه مسـکن زیرزمینی ترکیب می‌کند تا جذابیت، پایداری و شـمول شـهری را افزایش دهد. معیارهای شـاخص کلیدی، از جمله شـاخص‌های زیسـت‌محیطی، اجتماعی-اقتصـادی و جذابیت شـهری، برای ارزیابی اثربخشـی تلاش‌های توسـعه مجدد توسـعه داده شـده‌اند. مطالعات موردی از آلمان، بلژیک، فرانسـه و ایالات متحده، کاربردهای عملی و پتانسـیل تحول‌آفرین این اسـتراتژی‌ها را نشـان می‌دهد. یافته‌ها بر اهمیت پرداختن به محدودیت‌های اجتماعی-اقتصـادی، اصلاح محیط زیسـت و چالش‌های نظارتی از طریق برنامه‌ریزی مشـارکتی، حکومتداری نوآورانه و مشـارکت‌های دولتی-خصـوصـی تأکید دارند. این مقاله با شـناسـایی زمینه‌هایی برای تحقیقات آینده، از جمله پذیرش اجتماعی-فرهنگی مسـکن زیرزمینی، چارچوب‌های سیاسـتی خاص منطقه و فناوری‌های پیشـرفته اصـلاح، نتیجه‌گیری می‌کند. این مطالعه یک نقشـه راه جامع برای تبدیل مناطق معدنی به محیط‌های شـهری پر جنب و جوش، پایدار و تاب‌آور ارائه می‌دهد.

کلمات کلیدی: مناطق معدنی، فضاهای خالی شهری، مسکن زیرزمینی، جذابیت شهری.