A People-Centric Approach to Repurposing India's Coal Mines: From Frameworks to Action

CENTRE FOR A
People-centric Energy Transition

ashoka UNIVERSITY

CENTRE FOR A
**People-centric
Energy Transition**

Authors

Dr Aishwarya Ramachandran, Research Manager, ACPET
Mr Animesh Ghosh, Senior Research Fellow, ACPET
Mr Vaibhav Chowdhary, Director, ACPET

Design

Dr Piya Srinivasan, Manager, Communications, ACPET
Ms Bipashna Sharma, Communications Associate, ACPET

About Ashoka Centre for a People-centric Energy Transition (ACPET)

ACPET is a research-focused, transdisciplinary centre within Ashoka University, India, established to drive a sustainable, equitable, and "people-centric" shift towards net-zero emissions. It bridges the knowledge gap in energy transition by collaborating with industry and government to create scalable solutions, covering areas like renewable energy, policy, and technology. For further information about ACPET, please visit: acpet.ashoka.edu.in

About Ashoka University

Ashoka University is a private research university in Sonipat, Haryana, offering a liberal education in the humanities, social and natural sciences. It provides a multidisciplinary, interdisciplinary, and holistic education, offering a diverse and inclusive space for its students to think critically across disciplinary boundaries, express themselves creatively, and communicate with meaning for impact. For further information, please visit: ashoka.edu.in

Suggested Citation:

Ramachandran, A., Ghosh, A., Chowdhary, V., 2026, A people-centric approach to repurposing India's coal mines: From frameworks to action: Ashoka Centre for a People-centric Energy Transition, Delhi, Ashoka University, Sonipat, Haryana. (https://doi.org/10.5281/zenodo.19481102)

CENTRE FOR A
People-centric
Energy Transition

Table of Contents

CENTRE FOR A
People-centric
Energy Transition

CENTRE FOR A
People-centric
Energy Transition

Acronyms

AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
CC BY-NC 4.0	Creative Commons Attribution–NonCommercial 4.0 International License
CCO	Coal Controller Organisation
CIL	Coal India Limited
CLD	Causal Loop Diagram
CO_2	Carbon Dioxide
EIA	Environmental Impact Assessment
EnWM	Entropy Weighting Method
EU	European Union
FFA	Force Field Analysis
FGD	Focus Group Discussion
FPIC	Free, Prior, and Informed Consent
FPO	Farmer Producer Organization
GIS	Geographic Information System

GIS-MCDA	Geographic Information System – Multi-Criteria Decision Analysis
GoI	Government of India
ICMM	International Council on Mining and Metals
IFC	International Finance Corporation
ILO	International Labour Organization
IGF	Intergovernmental Forum on Mining, Minerals, Metals, and Sustainable Development
ISO 14000	Environmental Management Standards (ISO series)
L.I.V.E.S	Land and Technical Reclamation; Integrated Community Engagement and Empowerment; Viable Post-Closure Development; Ecosystem Rehabilitation; Regenerative Environmental Restoration; and Sustainability and Stewardship
LURA	Land Utilization Repurposing Application
MADM	Multi-Attribute Decision-Making
MAUT	Multi-Attribute Utility Theory
MCDA	Multi-Criteria Decision Analysis
MCDM	Multi-Criteria Decision-Making
MIF	Multi-Influence Factor

MGNREGA	Mahatma Gandhi National Rural Employment Guarantee Act
MLSA	Mined Land Suitability Analysis
MoC	Ministry of Coal
NGO	Non-Governmental Organization
NITI Aayog	National Institution for Transforming India
OCP	Opencast Project
PGIS	Participatory Geographic Information System
PMLU / PMLUs	Post-Mining Land Use / Post-Mining Land Uses
PPGIS	Public Participatory Geographic Information System
PRA	Participatory Rural Appraisal
PROMETHEE	Preference Ranking Organisation Method for Enrichment Evaluation
RECLAIM	Reach Out, Envision, Co-Design, Localise, Act, Integrate, Maintain
SDG/ SDGs	Sustainable Development Goal(s)
SDSS	Spatial Decision Support System
SECL	South Eastern Coalfields Limited

SES	Social-Ecological System(s)
SHG	Self-Help Group
SIA	Social Impact Assessment
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
UN	United Nations
UNDRIP	United Nations Declaration on the Rights of Indigenous Peoples
USA	United States of America
USGS	United States Geological Survey
WB	World Bank

Executive Summary

In India, the closure and transition of coal mines have significant implications for local economies, mining communities' livelihoods, and landscapes. Past rehabilitation efforts globally have largely prioritized technical remediation and environmental compliance, often overlooking the voices and priorities of affected communities. Recently, however, updated mine closure and repurposing guidelines from the Ministry of Coal (MoC), and the development of national-level frameworks like the Coal Controller Organisation's (CCO) L.I.V.E.S. and RECLAIM handbooks signal a shift toward more inclusive and community-oriented approaches.

Nevertheless, global research on post-mining land uses (PMLUs) still lacks a structured methodology for integrating local aspirations with scientific and spatial assessments. This report responds to that need by proposing a structured, multi-phase process grounded in participatory engagement, social-ecological systems (SES) analysis, and geospatial decision-making tools. The purpose of this study is to expand the discussion around mine closure and repurposing within the Indian context through:

A. Reviewing the domestic and global research literature on mine land repurposing, particularly methodologies for assessing the suitability of PMLUs.

B. Recommending a people-centric framework for assessing and implementing repurposing projects in India, rooted in a SES perspective.

The report begins with an overview of India's most recent coal mine closure and repurposing guidelines and policy landscapes, highlighting the current range of repurposing projects approved by the GoI and MoC. Next, we conduct an in-depth review of the global literature on the various methodologies used to assess the suitability of PMLUs. Having identified a disconnect between bottom-up community-based approaches and more technical or structured approaches, we argue for reconceptualizing post-mining landscapes as an SES. This entails envisioning India's post-mining landscapes as systems where ecological processes and human activities continuously influence one another through feedback loops allowing for structured assessments of mine lands that accounts for mine site and region-specific dynamics.

Synthesizing this information, we propose a three-phase, people-centric framework: (I) comprehensive site and stakeholder assessment (forefronting community priorities), (II) SES mapping and causal-loop modeling (matching community priorities to potential PMLUs), and (III) suitability analysis of each proposed PMLU (providing the evidentiary basis for the site's repurposing plan). Throughout the process, we stress the importance of integrating multiple opportunities for stakeholder feedback, particularly affected communities and local/ regional decision-makers.

Our proposed workflow begins by (re)assessing the mining site through mine closure reports, and any scientific and technical studies pertaining to the area to establish baseline conditions and identify environmental risks and socioeconomic constraints (e.g., development of informal settlements). Next, we strongly suggest understanding local stakeholder priorities (i.e., communities surrounding the mine, government officials like the district collector) through participatory methods such as rural appraisals, participatory GIS, and visioning exercises to capture diverse perspectives, particularly those of women and marginalized groups.

Next, stakeholder priorities must be matched with potential PMLUs using previously collected information to conceptualize the mine site as a social ecological system (SES) and its dynamic interactions with the surrounding areas. Following this, a suitability analysis based in fieldwork, stakeholder consultations, and/ or geographic information-based multicriteria decision analysis (GIS-MCDA) may be conducted to identify the most suitable locations for each proposed PMLU, based on environmental, economic, and social criteria (and corroborated through returning to stakeholders for feedback).

The workflow is designed to be flexible and responsive to changes in context; each phase operates along a spectrum of Low-Med-High complexity, allowing for differences in data availability and time/ resource constraints for stakeholder consultations. The outcome is an approach that helps align technically feasible land uses with community preferences and regional sustainability goals. In the report's annex, we include a curated list of mine repurposing projects previously undertaken in India and globally to demonstrate the range of domains they span, as well as an overview of the literature on mine reclamation and remediation processes which take place prior to, and set the precedent for, mine land repurposing.

Acknowledgements

We would like to thank Aakansha Singh, Varusha Khare and Tanya Kapoor for their assistance in developing early versions of the information contained in the manuscript and annex.

Introduction & Context

As coal-dependent regions increasingly transition away from fossil fuels, questions about how to responsibly close and transform coal mines have gained global attention (Pagouni et al., 2024). Abandoned coal mine sites pose significant ecological and public health risks, while also presenting untapped opportunities for land rehabilitation and socioeconomic revitalization. As the world's second-largest coal consumer and third-largest producer, India (having set a goal of achieving net zero emissions by 2070) must balance its growing energy needs with a transition away from fossil fuels. Operational mines in India currently occupy about 0.35 million (3.5 lakh) hectares of land, of which 0.2 million (2 lakh) hectares are likely to become available in the next 10 years through the closure of about 297 mines (Banerjee et al., 2024). The Government of India (GoI) and Ministry of Coal's (MoC) 2025 updates to India's mine closure guidelines identified 147 mines for closure by coal companies, with mine closure plans prepared and approved by the respective company boards.[1]

World-over, abandoned mines have been repurposed in numerous ways, including CO_2 removal, biodiversity enhancement, and economic revitalization, with successful case studies emerging from India and further afield, such as Germany, Australia, the USA, and China (Pearman, 2009) (see Appendix A for a selection of domestic and international examples). These projects not only include mine pits but also any land, infrastructure, water bodies, and other resources located within the mine boundaries. Repurposing abandoned coal mines offers a transformative opportunity to tackle environmental, social, and economic issues; however, additional research is required

[1] There are some conflicts across sources about the exact number - another announcement by Coal India Limited has identified 169 pre-2009 and 130 post-2009 mines, considered abandoned, discontinued, or closed. Meanwhile a 2024 report jointly produced by the consulting groups PwC and the Indo-German Energy Forum cites about 293 abandoned, closed, and discontinued mines in the country, based on a Ministry of Coal notification dated 7 February 2022. For more see: https://www.business-standard.com/india-news/299-mines-identified-as-abandoned-discontinued-or-closed-so-far-govt-124011200890_1.html; https://energyforum.in/fileadmin/india/media_elements/publications/Repurposing_Options_for_Coal_Mines_in_India/Repurposing_Coal_Mines.pdf

to illustrate the extensive array of potential opportunities and their applicability to the Indian context. Indeed, while successes in places like the German Ruhr Valley, for example, are very widely cited, they nevertheless have limited applicability to lower and middle-income countries, which are subject to limited local-level governance capacity, poor infrastructure, and lack of alternative employment and business opportunities (Measham et al., 2024). Given that any post-mining land use (PMLU) decision impacts various stakeholders, including corporations, workers, government, and local communities in the short and long term, such efforts must not only mitigate the loss of employment but also support economic diversification and sustainable development (Ronyastra et al., 2023). There is also a need to better understand how both the academic and grey research literature have tackled the question of repurposing from a methodological perspective to identify which approaches, tools, and datasets may be effectively brought together to bear upon the complex problem of equitably transforming a post-mining landscape.

Mine closure has historically been perceived and approached as a technical process focused on meeting regulatory requirements, taking an environmental engineering approach to reconstruct and rehabilitate mined landscapes for economic and natural land uses (Huang et al., 2022). In India and globally, there has increasingly been a move towards developing more holistic repurposing regulations aimed at benefitting mining communities; this has required a paradigm shift towards envisioning and co-designing repurposing projects with a wide range of stakeholders (Coal Controller Organisation, 2025b). More recently, social transition has emerged as a core component of post-closure land use, with an increasing emphasis on closely involving affected communities in the repurposing process (International Council on Mining and Metals, 2025). Such an approach includes prioritizing local and traditional knowledge, contending with the specificities of local biophysical and socioeconomic contexts, and emphasizing land uses to maximize benefits for local and regional stakeholders (Bainton & Holcombe, 2018).

As India continues to build on its current scientific mine closure and repurposing guidelines, there is a pressing need to clarify the most relevant methodologies and assessment criteria to inform repurposing efforts (as well as delineate how they differ from those used in reclamation or regeneration projects). There are several terms used to describe a wide range of post-mining activities which are geared towards addressing different aspects of the environmental, technical, regulatory, and socioeconomic consequences of mine closure. These include reclamation, remediation, rehabilitation, repurposing, and co-purposing, which differ in their scope and emphasis (see Table 1) (Grant et al., 2016; Holcombe & Keenan, 2020; Pagouni et al., 2024). Repurposing goals differ fundamentally from reclamation, remediation, and regeneration goals; repurposing is not just concerned with biodiversity and ecology, but also with economic viability, technical feasibility, social acceptance, and long-term sustainability (Keenan and Holocombe, 2020). Repurposing occurs after or alongside other activities in the mine closure process (like remediation and rehabilitation). Its main goal is to enable socioeconomic development of mining areas by transitioning the local economy and building on and/or establishing new forms of attachment to the site and region (Bainton & Holcombe, 2018; Holcombe & Keenan, 2020).

Table 1: List of post-mining activities and their definitions

Activity	**Description**
Rehabilitation	The return of disturbed land to a stable, productive and self-sustaining condition, after considering beneficial uses of the site and surrounding land. Reinstatement of degrees of ecosystem structure and function where restoration is not the aspiration.
Remediation	Often referring to abandoned mine sites, remediation aims to return sites to a physically and chemically stable state. This includes undertaking corrective actions to reduce environmental contamination to acceptable regulation-based standards.
Regeneration	Re-establishment of ecosystem structure and function to an image of its prior near-natural state or replication to a desired reference ecosystem.
Reclamation	Reclamation focuses on returning land and/or infrastructure to a state where economic, environmental or human uses are possible.
Repurposing	Repurposing utilises elements of the existing mining infrastructure (i.e. roads, mine housing, operational buildings) and the reconfigured aspects of the landscape (i.e. mine voids and mine features) for a different activity post closure.

Co-Purposing	Co-purposing consists of developing a beneficial activity on a site where operations or management relating to the primary business is on-going. In this report, we have included examples of concurrent or progressive reclamation of a closed area of an on-going operation that also demonstrate additional beneficial transitions beyond rehabilitation. Such practices look beyond closure to engage with possible post-mining land uses.

While mine land rehabilitation projects to enhance biodiversity have seen considerable success in countries like the USA and Germany, there is a pressing imperative for India to focus on socioeconomic revitalization and diversification in post-mining contexts. Mine closure practices began and were codified in advanced economies with mature mining industries, with emphasis on restoring the landscape and returning to the 'natural' pre-mining land cover (Limpitlaw & Briel, 2014). However, the cost of restoration may be far greater to rural communities in developing countries where infrastructure such as roads, clinics, and schools is urgently needed (and previously provided by mining companies). Moreover, given the significance of the coal industry in creating direct, indirect, and induced employment (through both formal and informal channels) in India, a vast majority of mine-adjacent communities are highly economically dependent on mining activities. This, in turn, affects the regions' livelihoods, infrastructure, environmental conditions, state revenues, and quality of life (Bhushan et al., 2025). As NITI Aayog has previously noted, coal mining regions have been transformed into "monoculture societies", and mine closures will not only cause significant unemployment among formal and informal mine workers but also significantly reduce the income of local businesses, force worker outmigration, and dampen local economic opportunities (Kamboj & Tongia, 2018; Mitra et al., 2024).[2] While earlier reclamation projects across India primarily focused on afforestation and plantations and have positive environmental benefits, they have

[2] In addition to localised impact on employment and migration, the closure of mines will also affect the Indian Railways, which is among the largest employers in the country, and relies significantly on the transportation of coal (accounting for nearly 50% of its overall income from freight services).

limited impact on employment and are insufficient to fully address the long-term social and economic potential of post-mining landscapes (Banerjee et al., 2024).

In this report, we review the domestic and international literature to identify frameworks, methodologies, and criteria that align with India's current coal mine closure and repurposing guidelines. We begin by discussing several policy and regulatory developments around mine closure and repurposing from the GoI. These documents were identified via recommendations from energy transition experts and government stakeholders. Next, we examine the global academic and grey literature discussing methodologies and frameworks to identify and assess the suitability of various repurposing options. We provide a summary of the main findings and gaps in the literature and identify pathways forward through introducing a new framework to assess the suitability of coal mine repurposing projects in India.

India's Mine Closure and Repurposing Guidelines

The most recent versions of India's mine closure guidelines demonstrate a significant shift from a narrow focus on technical and environmental remediation towards more integrated frameworks that include socio-economic and community-focused sustainability considerations. While Pagouni et al. (2024) have suggested that India's guidelines around PMLUs are limited to refilling the final mine pit with excavated materials, as of 2025, there have been several reforms to the guidelines including increasingly incorporating international best practices, environmental impact assessments (EIA), financial assurance mechanisms and emphasising domestic stakeholder engagement.

The socio-economic impacts of mine closure, especially on mining-dependent communities, are profound; these impacts include displacement, livelihood loss, and the loss of infrastructure and services previously provided by mining companies (e.g., medical care, schools). Mitigating these impacts requires participatory planning and long-term community engagement, though these are often inadequately implemented, or not developed far enough in advance of closure (Coal Controller Organisation, 2025a). Environmentally, while Coal India Limited (CIL) adheres to international reclamation techniques and standards like ISO 14000, a lack of standardised benchmarks and long-term monitoring limits effectiveness (Hilson & Nayee, 2002; Padma et al., 2008).[3]

The roles of government and private sectors are complementary yet often uncoordinated, with financial assurance mechanisms like performance bonds being underdeveloped. Insufficient socio-economic data, weak policy enforcement, and inadequate handling of legacy issues like abandoned mines illustrate the necessity of early, integrated planning, supported by robust regulatory frameworks, transparent financial tools, and inclusive multi-stakeholder collaboration to ensure sustainable post-mining land uses.

[3] ISO 14001 certification helps mining operations implement structured Environmental Management Systems (EMS), enabling compliance with environmental regulations, continuous improvement, and sustainable practices. CIL's own documentation highlights its efforts in environmental sustainability and adoption of ISO standards across its operations.

In India, updated scientific mine closure guidelines published in early 2025 emphasise that mines cannot be abandoned or backfilled alone, but must undergo a deliberate process of reclamation, regeneration, and ultimately repurposing to benefit affected communities (Ministry of Coal, 2025). These closure stages require technical planning alongside a robust system of criteria and frameworks to assess if a site is environmentally stable, economically feasible, socially acceptable, and technically suitable for future use.[4] The guidelines emphasise transforming mines to minimize the environmental footprint of closure, mitigate adverse impacts on local communities and ecosystems, and facilitate the preservation of natural habitats.

Repurposing options recommended by the GoI include agriculture, irrigation, pisciculture, development of eco-parks, tourism and recreation, arts, crafts and heritage, landscaping, waterbody conservation/creation, solar and green energy, and micro, small, and medium green industries. Projects should create local jobs and help people learn new skills during and after repurposing work, while also working closely with NGOs, mine workers, and local communities to design repurposing plans together. Where possible, these guidelines recommend drawing on local knowledge in the realms of a) developing arts, culture, and heritage-related projects; b) promoting local species, fruit-bearing plants, water conservation, wildlife conservation, flora and fauna conservation, and topsoil management; and c) creating horticulture, agriculture, and pisciculture spaces. The guidelines call for focused investments in skill development, livelihood diversification, and public services, requiring that at least 25% of the five-yearly escrow amount and 10% of the Just Transition allocation be used for community development and livelihood-related activities in consultation with district authorities, local institutions, and key stakeholders.

While mine repurposing efforts are at a relatively early stage in India, there is considerable enthusiasm about closely engaging post-mining communities in the project design and implementation. The development of the RECLAIM Framework by the MoC's Coal Controller Organisation (CCO), in partnership with the Heartfulness

[4] While not specific to coal mine lands, The Nature Conservancy has developed "SiteRight", a GIS-based web tool to identify low social conflict, low environmental impact land parcels for solar and wind projects in India, noting that a lack of careful planning can create land conflicts that will jeopardise investments and slow RE expansion.

Institute, recommends an explicit people-centric approach to community engagement and development in the context of mine closure (Coal Controller Organisation, 2025b). Drawing on principles of inclusion, long term responsibility, and shared decision-making, RECLAIM draws on resources such as the International Council on Mining and Metals (ICMM) Integrated Mine Closure Good Practice Guide (2022), International Finance Corporation's Performance Standards, United Nations Declaration on the Rights of Indigenous Peoples, International Labour Organisation (ILO) Convention 169, and Sustainable Development Goals (SDGs).

Moving beyond technical compliance with mine closure guidelines, RECLAIM provides recommendations to initiate and maintain consistent engagement with communities, local government, rural development programs, and NGOs. It recommends co-designing and implementing programs in basic infrastructure, local livelihoods/economies, human development (e.g., education, health), culture/heritage, and local governance and rights. There are 7 distinct phases in its model: Reach out, Envision, Co-design, Localise, Act, Integrate, Maintain (Table 2).

Table 2. The seven phases of the RECLAIM framework (table reproduced from report)

Letter	Phase	What it means	Tools	Purpose
R	Reach Out	Enter the community, listen, map who lives there and build trust.	Community Profiling Tool, Village Resource Mapping Tool	Baseline data on demographics, institutions, assets.
E	Envision	Facilitate a shared vision of life after mining – values, hopes, priorities.	Vision Tool, Goal-Setting Tool	Capture community aspirations and measurable targets.

C	Co-Design	Translate the vision into concrete plans, set goals, allocate responsibilities.	Focus-Area Setting Tool & Prioritisation Matrix, Development Planning Tool	Choose priority interventions, allocate resources.
L	Localise	Adapt plans to local governance, ecology, culture and existing institutions.	Ground Reality Check Tool, Risk & Opportunity Mapping	Validate feasibility against local conditions, flag constraints.
A	Act	Implement livelihood, infrastructure, health, and environmental actions with community participation.	Community Implementation Tracker, Participation & Inclusion Checklist	Monitor rollout, ensure inclusive execution.
I	Integrate	Hook closure activities into broader development schemes, create monitoring & learning systems.	Institutional Convergence Map, Sustainability System Builder	Link activities to existing schemes, set up monitoring & learning loops.
M	Maintain	Transfer ownership to local leadership, ensure long-term stewardship and upkeep.	Community Stewardship Planner, Measurement & Evaluation Dashboard	Hand over asset management, track long-term outcomes.

Most recently, the CCO's L.I.V.E.S handbook continues to take a structured and forward-looking approach to mine closure, focusing on the following themes: Land and Technical Reclamation, Integrated Community Engagement and Empowerment, Viable Post-Closure Development, Ecosystem Rehabilitation, Regenerative Environmental Restoration, and Sustainability and Stewardship (Coal Controller Organisation, 2025a). It notes the historic tendency to approach mine land reclamation, environmental restoration, and community development in siloes (also suggested by publications like (Côte et al., 2022; Huang et al., 2022; Measham et al., 2024), and that a dedicated repurposing plan to guide long-term land use and community enrichment was not considered part of mine closure. It also notes that historically there were few efforts to map pre-mining landscapes, challenging post-closure ecological restoration efforts.

The handbook recommends developing repurposing plans along with a mine closure plan *before* the start of mining operations, including baseline assessment of land use, ecological and topographic features, biodiversity, and the socio-economic profiles (e.g., health, infrastructure, demographics, income) of communities in the area. It also recommends developing a stakeholder engagement strategy, community development plan in collaboration with local NGOs and self help groups, and repurposing plans focused on mine land and infrastructure to maximise benefits to the community. Mine repurposing, which the handbook describes as "Viable Post-Closure Development" recommends using mined land, infrastructure, and resources to benefit communities and the environment. This definition has four key pillars: a) transforming degraded and mined out land, b) restoring pre-mining ecosystems through soil stabilisation, treating polluted water bodies, afforestation, and biodiversity enhancement, c) supporting communities to move away from a mining-centric economy to diversified livelihoods in small-scale industry, agro-based enterprises, and tourism, d) co-development through participatory planning, reusing infrastructure for community benefit.

The primary recommendations are to prioritise sustainable, long term economic opportunities for communities, diversifying local incomes beyond extractive industries, and developing multi-use repurposing projects. Ecological restoration – defined as increasing plant diversity, soil fertility, tackling water and air pollution, are positioned as requirements to be undertaken prior to socioeconomic repurposing projects.

Methodologies Used to Assess the Suitability of Coal Mine Repurposing Options

The global literature on mine site repurposing tends to focus either on multiple repurposing options at a single site or a single repurposing option at many sites; the decision to pick one over another depends on the motivations of the stakeholders involved (Giri et al., 2025). On one hand, mining companies, local communities, and local governments may require suitability assessments for fixed locations or specific areas. On the other, national/state governments, environmental organisations, or developers considering a particular project may want to know the range of locations the project may be suitable for: in such cases abandoned mine sites may be identified as potential sites, but also "wastelands" and other low social conflict areas (for example, see The Nature Conservancy India's tool SiteRight for siting solar and wind projects). For this report, which is focused on repurposing abandoned mine sites, we focus on the former line of inquiry. Research in this area most frequently involves the development of case studies attempting to demonstrate the use of spatial analysis and/or multicriteria decision-making approaches. A notable exception is the Indo-German Energy Forum and PwC's 2024 report proposing a matrix to recommend repurposing options for coal mines in India (with a specific focus on energy generation and storage solutions) - though there is no clear methodology indicated in the report.[5]

Multi-Criteria Decision Analysis Approaches

A variety of decision-making approaches have been developed and applied to assess the suitability of various PMLUs for closed mines. The most frequently used is Multi-Criteria Decision Analysis (MCDA),[6] a structured approach to evaluating and

---

[5] For more, see Daruka, Y., Gupta, S., Dash, S., Sengupta, A., Sharma, P., Shrivastava, J., Adhikari, D., Pathak, N., & Baden Powell, D. (2024). *Repurposing Options for Coal Mines in India*. PricewaterhouseCoopers Private Limited. https://energyforum.in/fileadmin/india/media_elements/publications/Repurposing_Options_for_Coal_Mines_in_India/Repurposing_Coal_Mines.pdf

[6] Note that the term Multi-Criteria Decision Making (MCDM) is often used interchangeably with MCDA. MCDA tends to emphasize a structured approach to decision making while MCDM refers to the overall process. Also note the use of the term Multi-Attribute Decision Making

prioritising multiple conflicting qualitative and/ or quantitative criteria in decision-making. MCDA supports decision-making when conflicting economic, societal, environmental, technical, and aesthetic objectives are involved, either by identifying the most preferred option, distinguishing between acceptable/unacceptable outcomes, or shortlisting and ranking options (De Montis et al., 2000).

MCDA has been applied extensively in the fields of mining and mineral processing, often to solicit and incorporate the views of stakeholders into decision-making in a quantitative, structured manner (Arratia-Solar et al., 2022; Measham et al., 2024; Sitorus et al., 2019). Early PMLU studies using MCDA include Soltanmohammadi et al. (2009; 2010), who developed a Mined Land Suitability Analysis (MLSA) framework based on Analytic Hierarchy Process (AHP),[7] Technique for Order Preference by Similarity to Ideal Solution (TOPSIS),[8] and Preference Ranking Organisation Method for Enrichment Evaluation (PROMETHEE),[9] to determine potential PMLUs (e.g., wildlife habitat, pasture, farmland, forestry, lake, sport field, park, residential, commercial, industrial, educational, sustainable community, and landfill) for a hypothetical mined land based on decision-makers' and experts' perspectives. The exercise was designed to demonstrate the efficacy of the Multi-Attribute Decision-Making (MADM) approaches to assess the suitability of repurposing projects based on economic, social, technical, and mine site criteria.

(MADM) is a subset of MCDA that specifically focuses on evaluating alternatives based on multiple attributes.

[7] AHP decomposes a complex decision into a hierarchy of goal, criteria, subcriteria, and alternatives, using pairwise comparisons to derive relative weights and check consistency. It aggregates those weights to score and rank alternatives, producing a decision that reflects both quantitative judgments and decision-maker preferences.

[8] TOPSIS ranks alternatives by measuring each alternative's distance to an ideal best and an ideal worst solution, preferring options closest to the best and farthest from the worst. It uses normalized criteria weights to compute these distances and produces a final relative closeness score for ranking.

[9] PROMETHEE is an outranking method that constructs pairwise preference indices based on criterion-specific preference functions and weights, then computes positive and negative outranking flows for each alternative. Alternatives are ranked by net flow (positive minus negative), allowing intuitive compromise decisions and partial incomparability when preferences conflict.

Based on the judgments of three mining experts in Iran, Masoumi et al. (2014) used fuzzy TOPSIS to rank post-mining land-use options and fuzzy AHP to determine the weights of criteria informing each land-use, to choose between alternatives when information is imprecise, vague, or uncertain. More recent studies such as Eshun et al. (2018) used PROMETHEE to determine the optimum mine closure alternatives for a mine in Western Ghana, engaging five mining experts to evaluate 40 criteria across socioeconomic, environmental and technical domains. In India, Singh et al. (2022) used AHP and TOPSIS to weight criteria (via stakeholder pairwise comparisons) and TOPSIS to rank repurposing options by closeness to an ideal solution—producing stakeholder-informed suitability rankings for closed opencast coal mine reuse. This study was based on data collected from seven decision makers, including research scientists, community representatives, and government officials. In Colorado, USA Demirkin et al. (2022) used multi-attribute utility theory (MAUT) to determine the repurposing projects which best reflect stakeholder preferences.[10] They created a sustainability survey (based on 17 social, economic, and environmental criteria) to capture stakeholders' (community, government, industry, mining experts) priorities across environmental, social, and economic dimensions of repurposing, and tested the robustness of their approach via sensitivity and scenario analyses.

Focusing specifically on renewable energy and circular economy repurposing projects, Krzamień et al. (2023), proposed a three-stage methodology and engaged 40 experts from four EU countries via the Delphi method. Structural analysis (MICMAC) was used to map technical variables,[11] ranking their influence and dependence, a morphological analysis (MORPHOL) recombined the vetted variables,[12] creating a

[10] MAUT is a decision-making method that converts each option's multiple attributes into normalised utility scores, weights those attributes by importance, and combines them into a single overall utility to rank alternatives. It makes trade-offs explicit and can incorporate risk attitudes and probabilities for decisions under uncertainty.

[11] MICMAC (Matrice d'Impacts Croisés-Multiplication Appliquée à un Classement) maps and analyzes the direct and indirect influence between variables in a system. It builds an influence matrix from expert judgments, computes powers of that matrix to capture indirect effects, and classifies variables into four categories—autonomous, dependent, linkage (relay), and driving (influential)—to identify key drivers and vulnerable factors for strategy or scenario planning.

[12] MORPHOL or Morphological Analysis is a problem-structuring method that explores complex, poorly defined domains by systematically generating and examining combinations of solution dimensions (parameters) and their possible values. It constructs a morphological box (grid) of dimensions × parameter values, uses consistency assessments or cross-

scenario space of feasible technology mixes. Lastly, MULTIPOL,[13] an MCDA approach, was used to evaluate each scenario against the European Green Deal, technology-readiness, European Union taxonomy, synergistic potential, sector-coupling, and circular-economy criteria. Also focusing on sustainable development and circular economy projects, Spanidis et al. (2025) investigated how "resilience" can be operationalised in post-mining transformation. Their proposed methodology merges quantitative stakeholder preference scoring (via Force Field Analysis) with weighted activity evaluation (via AHP) based in a case study on a Greek lignite mine, with seven mining research experts and practitioners.[14]

While not using a formal MCDA method, Padi & Purre (2022) created a decision model including a decision tree with restrictive criteria (created with mining experts) and decision-matrix with comparison criteria to choose the optimal reuse alternatives for three quarries in Estonia. Their matrix was created based on surveys with 93 stakeholders including landowners, local communities, governmental agencies, NGOs, universities, and environmental management and excavation companies.

GIS-based Multi-Criteria Decision Analysis

Another popular approach to determining PMLUs is the combination of GIS and MCDA (GIS-MCDA)[15], often with the goal of creating a user-friendly spatial decision support system (SDSS). The US Geological Survey's (USGS) Mined Lands Mapping Tool,

consistency matrices to eliminate infeasible combinations, and helps identify innovative, interdisciplinary, or non-obvious solution configurations without requiring quantitative scoring or optimisation.

[13] MULTIPOL is a scenario- and policy-analysis tool that systematically develops, compares, and tests multiple policy packages across plausible futures. It combines stakeholder-defined policy levers and criteria with scenario narratives or quantitative models to evaluate robustness, trade-offs, and unintended effects—helping identify policy mixes that perform well across diverse conditions rather than optimising for a single predicted future.

[14] Force Field Analysis is a problem-structuring and change-management tool that maps and balances forces for and against a proposed change. It lists and scores driving forces that support the change and restraining forces that oppose it, visualizes them (often as opposing arrows), and helps identify which restraining forces to reduce or which driving forces to strengthen to increase the likelihood of successful implementation.

[15] This is also sometimes called spatial multi-criteria decision-making (SMDM) (e.g., Arratia-Solar et al., 2022; Greene et al., 2011)

although focused on rehabilitation, revegetation, and hazard mitigation on mined lands in the USA rather than repurposing projects to benefit communities[16], incorporates GIS and remote sensing datasets for criteria in diverse domains including landscape features, environment and climate, infrastructure and mine characteristics, plants and animals, as well as social and management-related factors (O'Donnell et al., 2024). Giri et al. (2025) developed a spatial multi-criteria decision analysis (MCDA) framework to evaluate seven repurposing options for over 15,000 abandoned mines across Victoria, Australia. The study incorporated fourteen different spatial criteria, derived from an extensive literature review of site suitability studies and used entropy weighting method (EnWM) for criteria weighting as a substitute for stakeholder input. Focusing on Maharashtra, India, Bhushan et al. (2025) developed a "multi-criteria assessment framework" to identify mine clusters which were suitable for repurposing projects. Although the lack of a detailed description of the methodology makes assessing the approach challenging, the study used quantitative criteria across land availability (including area availability and forested land), closure feasibility (i.e., cost of closure), infrastructure and resource access (distance to water bodies, substations and thermal power plants) and renewable energy potential. The study also incorporated GIS analyses and visualisations to identify hotspots of transition risk and prioritise regions for green investments. Simpson et al., (2025) argue that PMLUs should be selected using specific planning lenses, particularly the SDGs, and offer a framework for integrating these considerations into a GIS-MCDA.

GIS-MCDA + Stakeholder Input

There are few studies in the PMLU literature that combine both physical criteria and stakeholder input (Servou et al., 2023). This is surprising considering that MCDA/MCDM has been used with GIS since at least the early 1990s in geography, planning and related fields (Greene et al., 2011). GIS provides a wide range of functionality to undertake comprehensive data collection, visualisation and analysis, while MCDM techniques enable integrating stakeholder preferences into the

[16] The US's Abandoned Mine Lands Economic Revitalization (AMLER) Program provides funding to select regions for economic development projects on abandoned mine lands - and has received $1 billion in grant funding to assist projects all across the West Virginia coalfields since 2016. However, details about the project selection methodologies are not publicly available.

decision-making process, making them very complementary methods (Greene et al., 2011; Malczewski, 1999, 2006).

Some recent examples suggest increasing interest in and utility of such approaches in the PMLU sector. Arratia-Solar et al. (2022) proposed a mixed-method conceptual framework to support decision-making about PMLUs (though not specifically repurposing): (1) a structured stakeholder-engagement process that captures diverse preferences for post-mining land-use attributes; (2) a GIS platform that assembles spatial environmental, socioeconomic, and technical data for the site; (3) a fuzzy-enhanced MCDM model that converts stakeholder judgments into weighted fuzzy numbers and applies methods such as AHP, TOPSIS, or PROMETHEE to rank alternative land-use scenarios. By normalising pairwise comparisons, assigning fuzzy memberships to attribute performance, and aggregating them through the chosen MCDM algorithm, the framework produces a transparent, reproducible ranking of viable post-mining futures.

Focusing on coal mine repurposing in particular, Servou et al. (2023) used the judgments of 10 mining experts to inform the development of weights for the criteria associated with a range of repurposing options, combining the results with GIS datasets to develop a geospatial land suitability model for PMLU at a surface lignite mine in northern Greece. The World Bank's cloud-based GIS tool–Land Utilization Repurposing Application (LURA) relies on extensive stakeholder input about parameters such as morphology, hydrography, geotechnical risks, socio-economic factors, and land value (both positive as added value and negative as remediation cost), as well as further parameters like permitting requirements or restrictions. However, the tool does not specify incorporating any GIS/remote sensing datasets, nor does it use any clearly specified MCDA approach to compare stakeholder inputs.[17]

Amaro et al. (2022) argue that current research on PMLU typically starts from a fully-specified decision problem—with a fixed set of criteria, alternatives and a predetermined MCDA method. The authors argue that this approach has two major drawbacks: 1) Limited transferability – because the problem is already "pre-structured," the same framework cannot easily be reused for a different mine, a different regulatory context, or a different stage of the closure-revitalisation process. 2) Insufficient stakeholder integration – many existing studies rely on technical criteria

[17]For more, see https://lurademo.geosysta.com/about

alone and do not embed a participatory weighting or a clear way to involve local communities, regulators, and owners throughout the decision-making chain. Indeed, the studies above demonstrate that there is a proclivity to engage experts (e.g., mine managers, researchers) and government decision-makers rather than communities.

Simpson et al. (2025) note that co-designing PMLU projects with key representative stakeholders is imperative, particularly in the light of national commitments to meet the United Nations' SDGs, to avoid the risk of a preconceived outcome. Rather than starting from a fully defined decision problem, the authors propose a framework that guides users from an early, low-detail stage through to a detailed, data-rich analysis (including participatory input and GIS analysis), making it potentially adaptable to many different mine sites and contexts. In Australia, Worden et al. (2024) argue for the importance of considering the regional context when developing mine-closure plans and developed a collaborative regional PMLU suitability assessment methodology that integrates stakeholder expertise, regional knowledge and a basic GIS-MCDA.

Non-MCDA Approaches

Stakeholder Workshops & Panels

Beyond the use of structured, quantitative MCDA approaches, some studies (particularly emerging from Australia) engage stakeholders (including communities) through alternative means including workshops, consultations, and panels. Everingham et al. 2018, for example, propose using a stakeholder panel as an effective and suitable strategy for achieving consensus on appropriate PMLUs in the context of mining rehabilitation. Noting the importance of involving local community members with a stake in responsible stewardship of mined lands, the authors suggest that a stakeholder panel is a recognised method for managing natural resources and catchment areas. They facilitate group discussions that consider different viewpoints across stakeholder groups, identify possible conflicts and areas of agreement, and offer tools and techniques for facilitating stakeholder panel decision-making.

Rolfe et al. (2018) suggest that mining operations in Queensland do not follow standardised approaches to engage with local and regional landholders about PMLUs. They conducted a series of workshops in which variations of a hypothetical post-mine land use exercise were posed to participants to provide a focal point for discussion via open-ended questions. Workshops aimed to assess landholders' perceptions, experiences, and local knowledge about neighbourhood and site level issues about mine closure and ex-mine land use, as well as PMLU options.

Everingham et al. (2020) suggest that while mining companies may use quantitative measures such as frequency of consultation to evaluate public participation in post mining land management processes, they are less effective in addressing fairness and competence of a process, as well as the trust, capacity, relationships, perceptions, and sense of ownership in the PMLU selection process. A wide range of participatory processes may thus be brought into consultative exercises depending on the stakeholder preferences and characteristics, ranging from communication (assisting the community to understand the alternatives, challenges and opportunities), to collaboration (partnering with the community to share responsibility, benefits and challenges), to ceding control to self-sufficient communities.[18] They highlight the importance of Social Impact Assessment (SIA) in particular as a method for identifying, evaluating, managing, and monitoring the social, cultural, and economic effects—both positive and negative, direct and indirect—of a project or planned change or intervention. SIA can guide the mine closure plan and serve as a foundation for a continuous post-mining participatory monitoring program that assesses the effectiveness of strategies in reaching the intended goals.

Outside Australia, Rosa et al. (2018) combined document analysis, interviews with communities, and a workshop with mine company staff to come to an agreed PMLU of a major bauxite mine in the Brazilian Amazon. They emphasise the value of the concept of ecosystem services (i.e., benefits that ecosystems provide people) for coming to consensus, because the concept's inherent focus on people provides a way to include community perspectives: "Taking an ecosystem services approach, mine closure planning maintains the focus on people's use of and dependency upon ecosystems rather than simply defending biophysical-oriented rehabilitation."

In India, policy documents such as the L.I.V.E.S Handbook recommend engaging communities early on as key collaborators, not just beneficiaries - and incorporating their historical knowledge about the landscape, particularly traditional agricultural practices, water management systems, and local plants and animals in the region. Specifically, the CCO recommends collaborating with communities to co-create a

[18] See Everingham et al. (2020), Table 1 for a list of profiles on several participatory processes such as community reference groups, visioning, social impact assessment, etc.

"pool of ideas" for sustainable PMLUs (with support and expertise from local government, NGOs, academic institutions, and businesses). At the Ashoka Centre for a People-Centric Energy Transition (ACPET), we have worked closely with post-mining communities in the discontinued mines of Rajhara, Jharkhand to develop suitable and sustainable pilot repurposing projects. Using a bottom-up approach, researchers engaged communities through multiple rounds of consultation and participatory mapping to co-develop a long list of repurposing projects based on the most pressing infrastructural and resource needs (ACPET, 2025a, 2025b, 2025c). In Rajhara, where many residents returned to subsistence agriculture following mining, the creation and refinement of the longlist eventually resulted in the development of a solar-powered drip irrigation system to pump water from a reservoir created by mining activities. A Farmer Producer Organization, dedicated to enhancing the community's connections to larger markets in the region, was also developed, and continues to be co-run by community representatives and a local NGO (ACPET, 2025a).

Incorporating Indigenous, Local, & Traditional Knowledge

Bainton & Holcombe (2018) highlight that Indigenous involvement in mine closure planning seeks to acknowledge their rights, incorporate Indigenous and traditional knowledge, and address concerns related to cultural heritage values in mine reclamation and post-mining land use. These practices can help restore cultural landscapes as communities actively apply their knowledge and experience of the environment. Additionally, post-mining land remediation or rehabilitation efforts can generate future economic opportunities for local groups connected to the land.

Rodon et al. (2025), however, highlights a growing scholarly literature criticising the ways in which local communities and their knowledge have been engaged, particularly Impact Assessment and Environmental Assessment processes, for being inadequate in achieving Free, Prior, and Informed Consent. They highlight several shortcomings, including the formal and often confrontational nature of these processes, inflexible timelines, the prioritisation of scientific and technical knowledge over Indigenous and local knowledge, and the fact that they usually occur only once during the later stages of project design, among other issues.

Worden et al., (2024) argue that one way to mitigate these issues is through adhering to established principles of collaboration and offer a framework to guide collaborative decision-making across the process of mine closure and PMLU planning. They highlight that local and/or Indigenous knowledge can serve to build reciprocity, one of the key principles of collaboration. For example, community members (who might not be able to contribute significant financial resources) could contribute local and/or Indigenous knowledge, while mining companies might provide financial support or expertise in mine rehabilitation, and local governments can offer venues for meetings and planning expertise.

Mapping Community Preferences, Perceptions, & Place Attachment

Another approach that has seen sporadic application in the PMLU literature is Participatory GIS (PGIS), a specialised form of participatory mapping that leverages GIS technology in the mapping process.[19] PGIS retains the core principles of community empowerment and local knowledge while providing additional tools for spatial analysis and data management (Brown & Reed, 2012; Corbett et al., 2016; Laituri, 2003; McCall, 2023).

Rolfe et al. (2018) developed a stakeholder workshop process for gaining consensus about priority issues and acceptable solutions in a hypothetical mine closure scenario. Stakeholders identified their preferred post-mining land use options using PGIS techniques (and paper maps), which were then compared to identify areas of agreement/disagreement. These were subsequently synthesised by experts into a map of proposed land uses, based on the most cautious outcome from each group.

Kivinen et al. (2018) used PPGIS to collect spatially explicit data on local stakeholders' perspectives on two post-mining areas in northern Finland. A key finding was that "the shadow of the mine"—aspects such as environmental impacts, uncertainties about their extent and duration, and knowledge gaps—can influence land use by local stakeholders well beyond mining sites and long after closure.

Svobodova et al. (2021) also used PGIS to understand and map place attachment in two communities in the Czech Republic, one next to a closed coal mine which has been closed and remediated into a recreational lake and the other adjacent to an active mine scheduled for closure in 2035. They found that place attachments are

[19] Note that the prefix 'public' is added to denote Public Participatory GIS (PPGIS) in cases where public input is emphasized in the mapping process.

flexible and can change, suggesting that, when the conditions are favorable, individuals can successfully adapt to industrial changes, even if these changes significantly disrupt their environment. They argue that the economic impact of energy transition policies unfolds locally, affecting policymakers and corporations planning on regional or national levels. They note that local acceptance and readiness for change, particularly with regard to place attachment, remain largely unexplored but should be considered crucial for the viability of energy transition proposals.

Methodological Gaps & Limitations

There is a constant refrain in both the academic and grey literature for community engagement and input in mine closure planning and decision making (Beckett & Keeling, 2019; Limpitlaw & Briel, 2014; Mborah et al., 2015; Measham et al., 2024; Murphy et al., 2019; Schneider et al., 2023; Sincovich et al., 2018; Stacey et al., 2010; Unger et al., 2020). Nevertheless, Rolfe et al. (2018) finds that despite widespread endorsement of participatory approaches and stakeholder engagement in closure planning, there is no clear consensus about effective ways of achieving genuine engagement. There appears to be a disconnect between bottom-up community-based approaches and more technical or structured approaches, with a marked paucity in social sciences and economics research on mining (Measham et al., 2024).

In their systematic review, Arratia-Solar et al. (2022) found 22 studies that applied MCDA techniques to PMLU planning, yet only two of these involved community stakeholders (and neither included a GIS analysis). Our review did not identify any studies using MCDA or GIS-MCDA that incorporate local community inputs into the decision analysis (i.e., identification of repurposing options, criteria selection, or model weighting). This matches broader trends globally; the Intergovernmental Forum on Mining, Minerals, Metals, and Sustainable Development found from its member survey that only 23% of governments reported a high level of community involvement in planning for closure and post-mining transition, while 37% reported no involvement of communities (Stevens & Brock, 2021). PMLU studies that involve stakeholder input are relatively uncommon, and the ones that do overwhelmingly focus on various experts or government officials rather than communities. Frameworks that do include community stakeholders in the PMLU selection process often consider their views last, after the perspectives of researchers and expert panels (e.g., Arratia-Solar et al.

2022). This disconnect might also help to explain the near-absence of public participatory GIS (PGIS) in the literature employing GIS-MCDA for PMLU assessment.

In addition to community input, there is a need for placed-based research to identify mutually-beneficial outcomes, as geographic context, cultural specificities, and stakeholder perspectives vary widely and cannot be addressed by a generic, top down approach to suggesting PMLUs (Foran et al., 2024; Perdeli Demirkan et al., 2022; Reeves et al., 2022). Coal mining has an immense, far reaching impact on neighbouring communities, not just in terms of employment, but by providing free/low cost fuel, social services (e.g., schools, medical drives), and spurring the development of local businesses to meet the needs of coal mine workers (Banerjee et al., 2024; Khanna et al., 2024; Mitra et al., 2024). When an individual mine closes, it is at the regional scale that transition is experienced; effective planning requires understanding the ecology of the surrounding area as well as regional surface and groundwater and their linkages (Côte et al., 2022). Thus, assessing the suitability and appropriateness of PMLUs for mine sites in India should require an understanding of the physical landscape at the mine site *and* the knock-on effects across the region (e.g., through identifying zones of impact). As research and policy documentation in the Indian context increasingly call for PMLUs based on the social-ecological dynamics of the surrounding region, there is a need for a suitability assessment methodology that integrates the biophysical, technical, and engineering aspects of mine closure with the social and economic aspects across local and regional scales (Bainton & Holcombe, 2018; Vivoda et al., 2019).

Post-mining Landscapes as Social-Ecological Systems

Mines affect every part of community life. When planning to close a mine, decision-makers need to think about how it will affect the economy, businesses and jobs, security, education and training, infrastructure and services, livelihoods, land and housing, health and the environment, demographic change, social participation and inclusion, basically, the well-being of the whole society (Ronyastra et al., 2023). While many PMLUs involve localised, micro-scale engineering projects related to water, soil, and vegetation, the longer-term social-ecological resilience of post-mining areas depends on forming positive feedback loops that reinforce environmental benefits and human well-being in the surrounding region (Cao & Tang, 2025). There is a need to transition away from highly technical, site-specific post-mining land management strategies that primarily focus on hazard mitigation and safety (Huang et al., 2022). Effective, just, and sustainable mine repurposing requires a shift from ecological engineering thinking to a *social-ecological systems* (SES) paradigm.

The concept of SES refers to integrated, interdependent systems comprising human (social, economic, cultural, institutional) and ecological (biophysical, species, ecosystem processes) components and the interactions between them. SES is a well-established conceptual framework that has seen increasing application and evolution over the last 20 years (Herrero-Jáuregui et al., 2018; Wang et al., 2025). Adapting the general SES framework proposed by Ostrom (2009), Cao & Tang (2025) developed a SES framework for understanding post-mining areas. While focused on restoration (not repurposing), their work highlights the importance of identifying components, hierarchical layers, and cross-level interactions of the post-mining system.

These developments also highlight how core SES concepts, such as resilience, might be mobilised to understand how effectively a post-mining area can absorb the multifaceted impacts of mine closure (e.g., economic outmigration, social instability, land degradation) (Aleksandrova & Timofeeva, 2021). The related concept of vulnerability, the combination of exposure, sensitivity, and adaptive capacity to changes, is also crucial to effectively managing the intense risks and changes associated with mine closure (Miller et al., 2010; Proag, 2014; Vázquez-González et al., 2021). For example, Agrawal et al. (2024) operationalised this definition to develop a coal vulnerability index as a way to understand how the burden of coal phase out is distributed across districts in India. While the authors did not work within an explicitly SES framework, their work demonstrates that SES-related concepts are already being used in the Indian post-mining context.

It is also worth noting the connections between SES and the ecosystem services (ES) framework. The latter attempts to describe the benefits people obtain from ecosystems, provisioning (e.g., food, water), regulating (e.g., climate, flood control), cultural (e.g., recreation, spiritual), and supporting (e.g., nutrient cycling), that sustain human well-being and economies (Baker et al., 2013; Daily & Matson, 2008). SES and ES are complementary frameworks: SES provides an integrated lens on the coupled human–environment components, interactions, governance, and feedback, while ES translates ecological functions within that system into tangible benefits for people. Using them together links system structure and cross-level dynamics (i.e., SES) to the supply, demand, trade-offs, and valuation of benefits (i.e., ES). This can improve diagnosis, stakeholder engagement, spatial planning, and adaptive management of post-mining landscapes. Indeed, the conceptual language of ES has been found to help structure community engagement around agreed-upon post-mining land uses by focusing on the services that are most important to local communities (Rosa et al., 2018).

In the context of post-mine land repurposing, it is important to consider how each proposed PMLU might fit within and affect the existing SES that the mine site is embedded in. Visualising the structure of the SES helps test and clarify system understanding and identify potential feedback (both positive and negative). One way of accomplishing this is through qualitative systems dynamics modelling, a method that maps and analyses the feedback loops and causal relationships within complex systems using non-quantitative diagrams and narratives (Egerer et al., 2021; Valencia, 2020). This is often done through participatory group modelling exercises focused on co-constructing a causal loop diagram (CLD), a visual tool used to represent the feedback relationships among variables in a system (Figure 1). A CLD consists of variables (nodes) connected by directed arrows that indicate causal influence; each arrow is labeled with a polarity (+ or −) to show whether the influence is reinforcing (same direction) or balancing (opposite direction). Loops formed by these connections are classified as reinforcing or balancing, revealing how effects propagate and how system behavior arises over time. CLDs are a key tool in systems analysis because they make it possible to "map" the complexity of a problem and avoid assuming linear relationships between elements, instead revealing cause-and-effect dynamics

(Haraldsson, 2004). By visualising feedback mechanisms, CLDs clarify both structure and processes within a system and facilitate transfer of system understanding. They also provide a language for expressing the dynamic, interconnected nature of the world; linking multiple loops creates a coherent story about a particular issue (Franz, n.d.).[20]

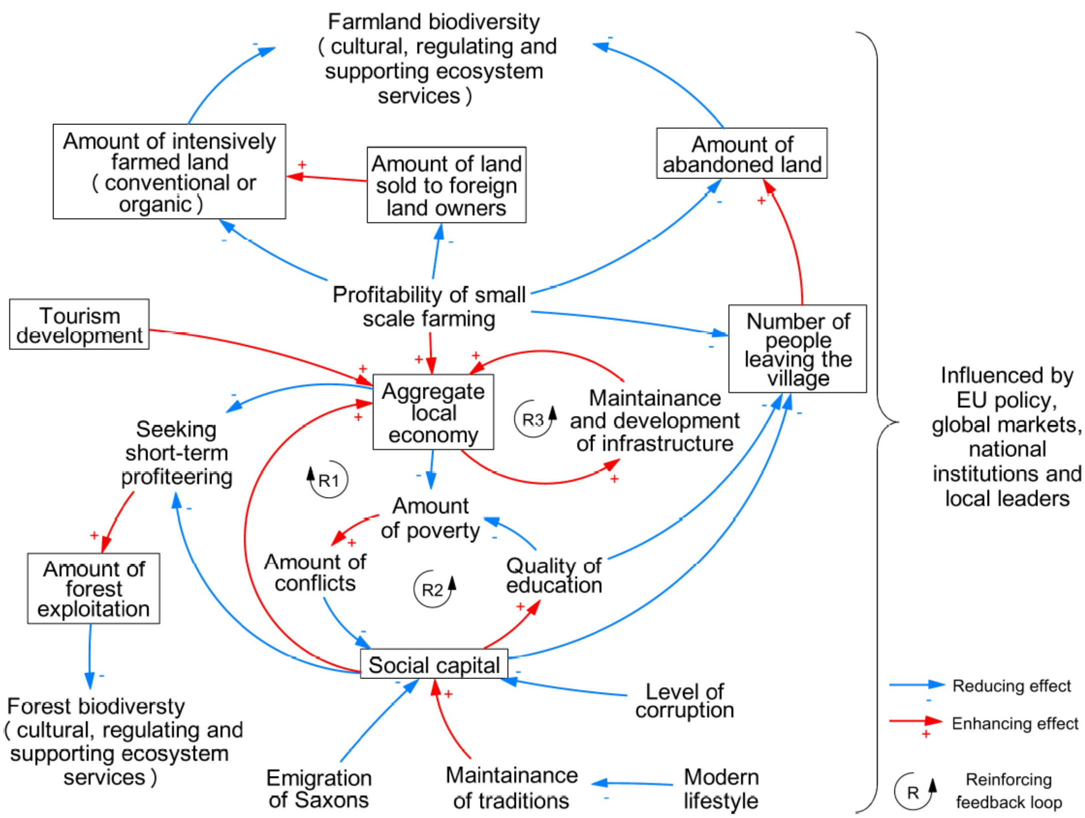

Figure 1. Example causal loop diagram summarising the dynamics of the regional social-ecological system in Southern Transylvania (Hanspach et al., 2014, Figure 5). This content is licensed under a Creative Commons Attribution-NonCommercial 4.0. International License (CC BY-NC 4.0). To view a copy of this license, visit https://creativecommons.org/licenses/by-nc/4.0/.

[20] See Franz (n.d.) For a detailed summary of the theoretical background and application of CLDs in sustainability.

In recent years, CLDs have been used to understand the social-ecological dynamics of a variety of topics, including groundwater dynamics (Bouchet et al., 2022), progress and impacts on the SDGs (Downing, 2022), human-wildlife governance (Kansky et al., 2025), the Water-Energy-Food-Ecosystems nexus (Giordano et al., 2025), and climate adaptation (Hanf et al., 2025). Downing (2022) describe the act of creating a CLD as an iterative process, with iterations consisting of: "a) identifying the different elements of the system and their causal connections; b) reflecting on the dynamic patterns that would play out from the feedbacks at a system level; and c) validating the connections identified by using adequate sources (literature, data, etc.)." This is often accomplished by participants drawing box-arrow style figures using pen and paper, but more complex software tools are also used.[21]

Several free web-based tools can facilitate this process, such graphViz (https://graphviz.org/), InsightMaker (https://insightmaker.com/), and LOOPY (https://ncase.me/loopy/). The latter two allow users to draw elements and links in their browser to construct systems models, identify feedback loops, and interactively simulate their dynamics. The exercise of co-creating CLDs not only helps stakeholders and researchers understand the complex contexts they are working within but facilitates the identification of leverage points for positively impacting the system (Giordano et al., 2025). In the context of PMLU planning, this can be used to think through how a proposed PMLU (or set of PMLUs) might impact the surrounding SES, thereby reducing the potential for negative feedback loops while promoting positive ones.[22]

[21] Hesketh et al., (2024) piloted the use of a systems dynamics modeling approach to develop PMLU planning, but with the goal of quantitative modelling and simulation tool rather than a qualitative approach to understanding PMLUs as SES.
[22] Iteratively thinking through hypothetical scenarios in a group setting has been shown to be highly effective in PMLU planning (Rolfe et al., 2018)

A People-Centric Approach for Assessing Mine Repurposing Projects in India

In response to the global research literature on PMLUs and the most recent policy developments in India on mine closure, we propose a people-centric approach synthesising both bottom-up and top-down methods to assess the suitability of mine repurposing projects in the Indian context. The driving goals of our approach are to:

- Front-end community input and priorities, with multiple opportunities for feedback throughout the process, building trust and confidence.
- Bridge the gaps between community and participatory approaches and GIS-MCDA.
- Analyse post-mining areas and potential PMLUs as SES.

Our approach is structured in three overarching phases, developed in line with recommendations from Ronyastra et al., (2023) and Rosa et al. (2018) who emphasize that early attention be given "...protecting environmental quality, aligning local and regional demands for future land use through land rehabilitation, and creating a sustainable positive legacy for the communities (Rosa et al., 2018)." These phases (see visual depiction in Figure 2) include I) compiling relevant information about the mine site, relevant stakeholders, and the regional context, II) understanding the (social-ecological) system the mine site is situated in, and III) using these steps to develop PMLU recommendations that are both physically appropriate for the site and match stakeholder needs and priorities.

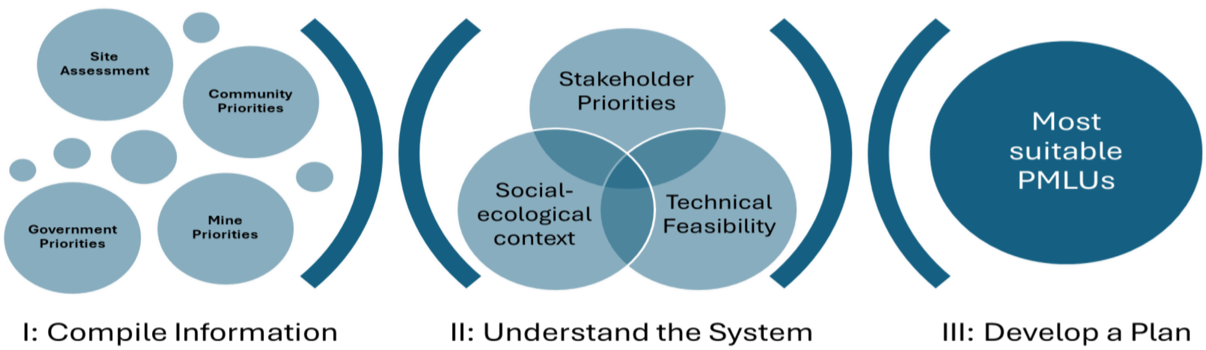

Figure 2. Three phases of a people-centric approach to coal mine repurposing.

These three phases can be broken down into smaller steps, (Figure 3), which we discuss in the following sections. However, we stress that these are intended as recommendations, not a one-size-fits all prescription. Our framework is designed to be flexible and responsive to changing context; each step operates along a spectrum of Low-Medium-High complexity, allowing for differences in data availability and time/resource constraints for stakeholder consultations.

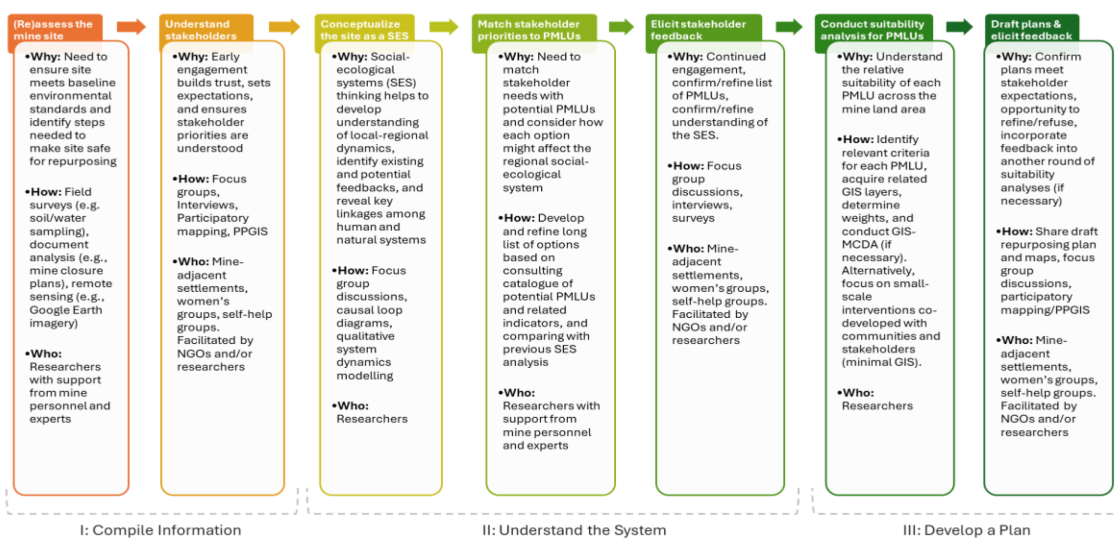

Figure 3: Summary workflow and associated objectives of a people-centric approach to coal mine repurposing.

Phase I: Compile Contextual Information

(Re)assess the Mine Site

A fundamental prerequisite for any repurposing project is ensuring that the mine site is in a safe, stable condition, as failure to do so could jeopardise any future developments on the site (Ronyastra et al., 2023). Recent guidelines from the GoI outline the need for mandatory incorporation of restoration, remediation, and regeneration measures into mine closure plans.[23] Before a closed coal mine can be transformed into a new productive use, it must first meet baseline environmental standards, including soil health, terrain stability, contamination risk, and surface structure. The foundational criteria associated with reclamation and remediation thus determine these baseline standards and assess whether repurposing is feasible in the first place.

In India, many mines being considered for repurposing today were closed in the 1990s or earlier. In these cases, it's vital to know what happened during closure and how conditions may have changed since. For example: What is the current state in terms of top-soil management, overburden handling, backfilling and grading, drainage and erosion control, water quality assessment, and soil stability? Have mine water bodies been created since discontinuation, and are they being used? What is the site's vegetation state, and is it used for agriculture, forestry, or other? This is a widely addressed subject in the research literature, and Annex B provides an overview and summary of the primary criteria considered in such assessments, as well as how studies define and operationalise them.[24]

This process of assessing (or reassessing) the mine site will primarily involve researchers, experts, and mine personnel. It may also benefit from local knowledge from mine-adjacent communities. Activities might include (but are not limited to):

---

[23] MoC, January 2025 Guidelines.

[24] Annex B is not intended as a comprehensive list of all possible criteria associated with post-mining land management strategies, as the focus of this report is on repurposing. For a more comprehensive review, see Pagouni et al. (2024).

- Acquiring mine closure plans and reading them to understand the characteristics of the mine, when it was closed, and what remediation or rehabilitation steps were carried out.
  - In the case of Indian mine closure plans, details are also included about the extent of formal and informal settlements present on mine lands, which drastically impacts the availability of space for larger-scale repurposing projects.

- Conducting fieldwork (e.g., soil/water/geotechnical surveys) to assess the state of the mine lands including safety hazards, slope stability, water and soil quality, etc.
  - In addition to consulting with mine personnel or geotechnical experts, these activities could include engaging neighbouring communities intersecting with the mine land. In India, for example, mine closure plans for underground mines abandoned during the late 20th century in now densely populated areas often include a consultation with residents situated close to where mining activity previously occurred.

In India, mine closure plans tend to be in disparate locations and offices, and available only in paper (or scanned PDF) format. To facilitate the use of the valuable information contained in these documents, our approach includes building an Indian mine closure plan database that organises and summarises a variety of attributes about each mine site. The database includes general information such as mine type, operating company/owner, date closed, geographic coordinates, lease-hold area, etc., as well as specific information such as presence and legal status of any settlements, status of environmental clearance, mining infrastructure, and the estimated monetary cost of fully closing the mine to meet all regulatory, environmental, and social obligations. We have also provided a rating for each mine, intended to guide the level of technical complexity taken in the eventual suitability analysis (see Phase III, below). Higher-rated sites typically cover larger areas and have sparse populations, enabling more sophisticated, data-heavy GIS-MCDA analyses. Lower-rated sites tend to be smaller and more densely populated, so simpler, low-tech strategies—such as small-scale interventions co-designed with local communities and minimal GIS use—are more suitable.

Understand Stakeholder Priorities

The second objective of our approach involves understanding the needs, aspirations, values, and preferences of the communities affected by mine closure. While all stakeholders are important, we focus on communities because in this step to ensure their perspectives are recorded and have the highest potential to influence the course of the repurposing project. Building trust and collaborative relationships with communities is not only the ethical thing to do (particularly from a Just Transition perspective) but increases the chance that the eventual PMLU project(s) are successful and sustainable in the long-term. This is also particularly important considering community-focused mine closure and repurposing guidelines receiving explicit support from government organisations such as the MoC's CCO, and regional subsidiaries. This process should closely involve personnel from local NGOs and universities in addition to collaborating with mining staff from the associated subsidiary. As mentioned previously, the L.I.V.E.S. handbook and RECLAIM framework provide comprehensive examples and guidelines for collecting community-based work in the context of India's mine closure. Activities may include:

- Focus group discussions
- Visioning exercises to imagine future scenarios
- Participatory mapping
- PGIS to understand place attachment/detachment
- Compiling district- or village/grampanchayat-level development priorities/plans

Many of the activities identified above can be conducted as part of frameworks such as Participatory Rural Appraisal (PRA), which prioritise participatory data collection processes and community ownership and sharing of knowledge (Chambers, 1994b; Narayanasamy, 2009). PRA has been widely practiced in India for several decades, particularly in rural development and community planning initiatives including the Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA) program, which utilises participatory planning processes at the gram sabha (village assembly) level to identify and prioritise works to be undertaken each year. Similar participatory methodologies can be effectively applied to mine repurposing contexts, as PRA employs techniques such as social mapping (depicting household locations, community institutions, and social relationships), resource mapping (identifying natural resources, land use patterns, and infrastructure), transect walks, seasonal calendars, and FGDs to systematically gather community perspectives (Chambers, 1994a). These tools will likely enable communities adjacent to closed mine sites to articulate their vision for post-mining land use, identify livelihood priorities, and highlight concerns related to environmental restoration and economic opportunities associated with mine repurposing initiatives. A key point in this step is to avoid conceptualising 'communities' as homogenous entities. Communities are themselves diverse, with their own social structures and internal politics. It is thus important that this step attempts to capture the voices of all segments of the communities (e.g., women; marginalised groups).

While understanding community priorities is crucial, the research literature discussed above emphasises understanding both the site-specific and regional context of the mine (and their interactions). Thus, this step also needs to involve gathering other local stakeholders' input, including government officials such as the District Collector, who is responsible for supervising development planning and revenue administration for the district. This information provides invaluable context for aligning potential PMLUs with existing plans. Other stakeholders to consult include mine personnel, many of whom may have longstanding relationships with surrounding communities and a deep understanding of the social-ecological interactions within and around the mine site.

Phase II: Understand the System & Build a Shortlist

Conceptualise the Mine Site as a SES

The next objective is to match the priorities identified through the aforementioned stakeholder consultations with technically feasible PMLUs. In order to do so, it is necessary to first conceptualise the mine site as an SES with dynamic interactions with the surrounding areas. This could involve the use of qualitative systems dynamic modelling approaches, specifically the co-construction of a causal loop diagram (CLD) describing the characteristics of the mine site as an SES (see above for specifics on this approach). Ideally, this should be an iterative process, involving a cross-sectoral workshop with community representatives, mine closure planners, local government, NGOs, and relevant technical experts (ecologists, hydrologists, landscape planners, agronomists) with facilitation by researchers. However, time constraints may necessitate researchers collating and synthesising the information collected from stakeholders themselves.

Match Stakeholder Priorities to Potential PMLUs

Once consensus has been reached on the CLD and its adequate representation of the SES, the next step is to identify potential PMLUs that match the priorities identified by communities. To facilitate this, we have developed a catalogue of PMLUs based on 2025 GoI guidelines and domestic and international literature. Each PMLU has been assigned a sector (e.g., energy, infrastructure, agriculture, etc.) and scored for several indicators related to economic/financial constraints, environmental impacts, and societal considerations (e.g., the specific Sustainable Development Goals addressed by each PMLU). By searching/filtering the PMLU catalogue and comparing this with their understanding of the SES, researchers can develop a longlist of potential PMLU options for the mine site in question. This longlist should then be refined through a screening process, based on existing knowledge of the surrounding landscape.

For example, if communities highlight the need for consistent electricity supply, the researchers might identify wind farms, solar farms, or pumped hydroelectric energy storage as potential PMLUs. However, discussions with local experts and/or screening analysis of publicly available wind speed data (e.g. globalwindatlas.info) might show that wind power is not an appropriate option for the site. The screening process should also involve revisiting the CLD to identify how each PMLU on the list might affect the existing SES (i.e., identifying potential social-ecological feedback loops that could amplify vulnerability or resilience).

Elicit Stakeholder Feedback on Proposed Shortlist

Once a shortlist of potential PMLUs for the mine site has been developed, this must be validated with the communities involved and other regional stakeholders. This can be done via FGDs and public meetings, eliciting feedback, filtering out unsuitable options. At this stage, it is essential to clearly communicate how initial consultations during Phase I were interpreted to select the list of PMLUs, and the implications of each project for community development. This may include presenting the researchers' current understanding of the regional SES (verbally or by sharing CLDs or other visuals) and updating it based on feedback. In addition to upholding ethical standards through reaffirming consent and transparent decision-making, discussing the shortlist and how it was developed prior to developing plans reduces the chances of later conflict.

Phase III: Develop a Site-specific Repurposing Plan

Conduct a Suitability Analysis

The goal of this phase is to identify the most suitable areas of the mine site for each PMLU on the stakeholder-approved shortlist, and to use this to develop a repurposing plan. The first step involves conducting a suitability analysis of each PMLU based on multiple biophysical and social criteria. The level of complexity of the suitability analysis should match the specific context of the mine site in question. For example, mine sites with smaller areas and dense populations are likely a better fit for low-tech approaches (i.e., small-scale interventions co-developed with communities and limited use of GIS)[25]. Sites with larger areas and limited human settlements would allow for a more complex, data-intensive GIS-MCDA. In cases where the shortlist consists of only one or two PMLUs, it may be sufficient to conduct a GIS-MCDA for each PMLU and manually resolve spatial conflicts in any areas where both PMLUs are highly suitable. In cases with more than two PMLUs, however, the GIS-MCDA may benefit from the use of conflict resolution algorithms such as Multi-Objective Land Allocation (Eastman et al., 1993). In either case, the GIS-MCDA should follow standard processes discussed in earlier sections of this report, tailored to the specificities of the mine site in question.

The first step in a suitability analysis based on GIS-MCDA should involve defining decision criteria for each PMLU being considered and compiling a set of related spatial data layers. These may include maps of ecosystem services or stakeholder values that come from PGIS exercises, and information about soil contamination, topography, hydrology, flood zones, land tenure, proximity to markets/roads, land cover, and ecosystem services. The values of each layer will need to be standardised to a consistent spatial resolution, coordinate reference system, and suitability scale (e.g., 0-1), either through reclassification and/or fuzzy membership functions. The latter step will have to be taken for each option being considered, since the suitability of a

[25] See ACPET's repurposing projects in Rajhara, Jharkhand for an example of a low-tech approach to suitability analysis in India (ACPET, 2025c).

criterion can vary significantly among different PMLUs (i.e., steep slopes may be highly suitable for eco-parks but highly unsuitable for solar parks).

Next, weights must be assigned to all criteria for each PMLU using expert interviews, surveys, or workshops. Where time/ funding prohibits this, weights may be determined based on existing literature and insights from previous qualitative system dynamics modelling. As discussed previously, AHP is a straightforward method for determining weights with wide application in MCDA literature. However, it assumes that the criteria being weighted are independent of each other (Saaty, 2013), an assumption that is unlikely to hold for many PMLUs. For example, slope is strongly related to flood risk, erosivity, and surface roughness, all of which may be included as criteria for a single PMLU. Other weighting procedures that capture interdependence among criteria may be more useful, particularly for capturing social-ecological dynamics. Analytic Network Process (ANP), a method accounting for inter-dependence among criteria and theoretically rigorous (Saaty, 2006), is known to be complex and difficult to communicate to stakeholders, potentially limiting its broad application. Another approach is the Multi-Influence Factor (MIF) technique, which focuses on interdependencies in a much simpler way than ANP and is useful when stakeholder comprehension and legitimacy are priorities. While MIF is less theoretically substantiated, it has seen increasing use in groundwater potential mapping (U. Khan et al., 2021; Nasir et al., 2018; Rane & Jayaraj, 2022) and land use planning, including in India (Rane et al., 2024; Singh et al., 2021), and may offer a potential 'middle way' between AHP and ANP. Depending on project duration and site complexity, this step could involve developing a hybrid approach (e.g., MIF for initial transparency, then sensitivity testing with ANP) followed by sensitivity analyses.

Draft Plans & Elicit Stakeholder Feedback

The spatial outputs of the GIS-MCDA should be used to locate the most suitable areas for each PMLU under consideration, applying constraints (e.g., 'no-go' areas) and multi-objective land allocation strategies for resolving areas with conflicting suitabilities (Masoudi et al., 2021; Rahnama, 2023). The resulting draft maps and plans should be presented to stakeholders for final validation to confirm that spatial siting, management rules, and expected benefits meet expectations and that stakeholders understand the potential impacts (positive and negative). This step should be used as a formal opportunity for acceptance, revision, or refusal so that stakeholders (particularly affected communities) can veto options or request alternative designs.

Conclusions and Next Steps

This report has several aims: to discuss the evolving policy landscape pertaining to mine closure and PMLUs, to provide an overview of the main methodologies used to assess the suitability of PMLUs, and to propose a people-centric framework for repurposing India's abandoned coal mines into sustainable, community-driven PMLUs. The review of domestic and international literature, combined with an analysis of the most recent updates to India's mine-closure guidelines, makes clear that repurposing abandoned coal mines is a socio-ecological transition that must be anchored in community priorities.

While at the level of the state, conventional frameworks centred around technical and biological reclamation have been most common, in India and beyond (particularly places like Australia) there has been a growing interest in repurposing mine lands to benefit mine-adjacent communities. In 2025 alone, India saw the publication of community-centric recommendations by the MoC as well as the CCO (i.e., the RECLAIM and L.I.V.E.S. frameworks). These guidelines identify green energy and industries, and projects centred around community development as national priorities for repurposing projects. Nevertheless, the remediation and repurposing recommendations they provide may be entirely relevant for mines previously abandoned in the country, which have already seen the extensive development of informal settlements in surrounding areas. Thus, while these resources set a new precedent for mine closure and PMLUs in the country, they have greater relevance for future mine closures.

There is extensive research literature on PMLUs that is robust, particularly when discussing the technical and scientific aspects of mine closure. Socioeconomic impact assessments remain relatively rare, especially consultations with communities in post-mining areas.[26] Where stakeholder perspectives are solicited, they are most frequently integrated into the decision-making process via structured, quantitative techniques falling under the broad domain of multicriteria decision analysis (MCDA). Studies using these approaches tend to mainly incorporate the perspectives of researchers, mining personnel, and geotechnical experts. Moreover, even while participatory methods and stakeholder involvement are championed in mine-closure

[26] A notable exception to this is a series of research studies produced by the Centre for Social Responsibility in Mining based in the University of Queensland and cited throughout this report. See, for example, Arratia-Solar et al., 2022; Bainton & Holcombe, 2018; Rolfe et al., 2018.

planning, there is still no agreed-upon set of protocols for fostering consistent, in-depth engagement. A gap persists between grassroots, community-led initiatives and more technical or formalized processes, and research from the social-science and economics disciplines on mining remains notably scarce.

There is a thus pressing need for a “people-centric” framework for assessing the suitability of PMLUs, particularly one which is relevant to the Indian context. We propose an approach integrating spatial-decision tools with social-ecological systems (SES) thinking. Thinking about post-mining lands as SESs is particularly important as it enables the identification of PMLUs which are not only suitable to the specificities of the mine site, but in line with more pressing socioeconomic needs faced by surrounding stakeholders, including mining communities. This is of salience for India where 32% of the country’s land is affected by degradation, and 25% undergoing desertification. Careful restoration and use of post-mining lands, which have previously undergone significant degradation, can alleviate some of this significant threat (S. Khan, 2024).

The proposed three-phase, people-centric workflow— (I) comprehensive site and stakeholder assessment (forefronting community priorities), (II) SES mapping and causal-loop modeling (matching community priorities to potential PMLUs), and (III) suitability analysis of each proposed PMLU (providing the evidentiary basis for the site’s repurposing plan)—offers a transparent, adaptable pathway that bridges bottom-up aspirations with top-down regulatory requirements. It overcomes the disconnect between community inquiry, GIS, and MCDA approaches used in the PMLU literature through additional steps such as:

- Soliciting community and local stakeholder engagement first to understand their needs as well as the local context.
- Matching needs to PMLUs to create a project longlist.
- Eliciting feedback about project longlist.
- Systematically create transparent suitability criteria for each PMLU.
- Validate final maps with communities, mining companies, and other relevant stakeholders.

The workflow is designed to be flexible and responsive to changes in context; each phase operates along a spectrum of Low-Med-High complexity, allowing for differences in data availability and time/resource constraints for stakeholder consultations (Figure 4). When applied consistently, this approach can generate repurposing options that are not only technically feasible, environmentally sound, and economically viable but also deliver tangible livelihood benefits while preserving sociocultural ties to the landscape.

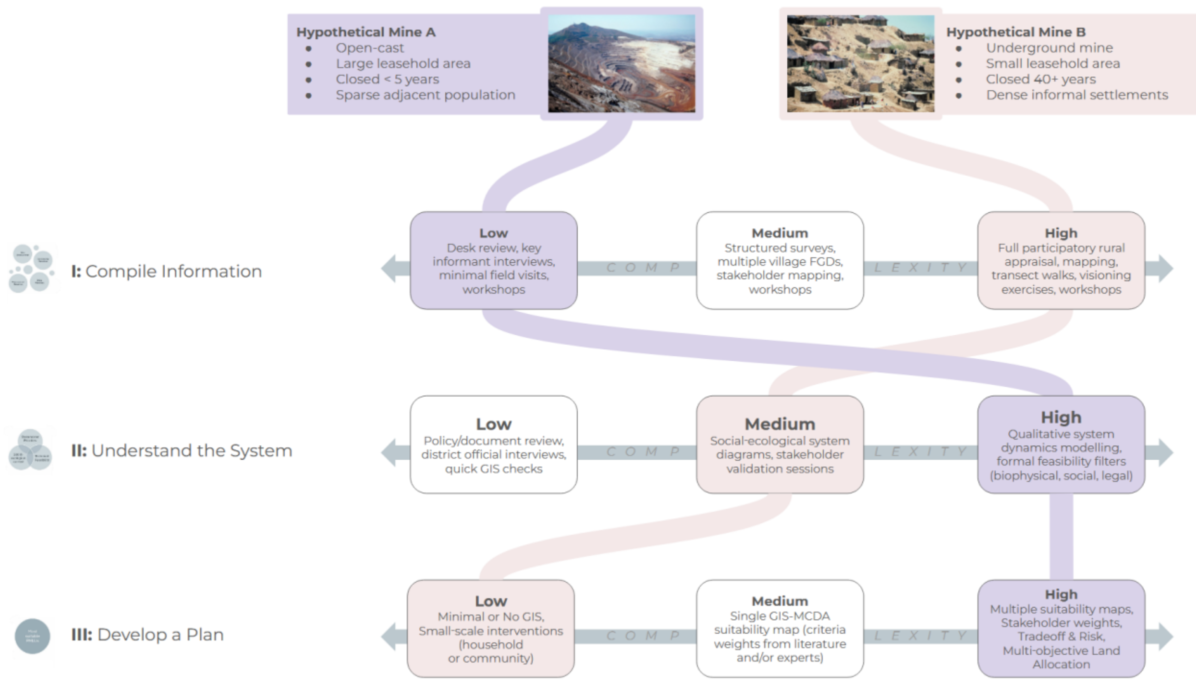

Figure 4. Diagram demonstrating the flexibility of each phase of the framework, and how the workflow can be modified to allow for differences in data availability, time /funding, and the specific characteristics of each mine site.

While the PMLU literature describes a wide array of repurposing options (e.g., solar farms, pumped-hydro energy storage, aquaculture, or eco-tourism) and related criteria (e.g., soil-health parameters, slope-stability thresholds, water-quality limits, job-creation estimates, governance checks), studies seldom agree on definitions, measurement methods, or weighting techniques. Consequently, decision-makers lack a coherent framework for comparing alternative options. This gap is especially pronounced in India, where repurposing policy and methodologies are still nascent and projects have yet to follow a standardised approach. Our approach is designed to facilitate more direct uptake of community perspectives collected in the field on the planning, execution, and monitoring of PMLU schemes—an area which remains underexplored, and one in which India could lead internationally. The proposed framework is intended to be transparent in structure and process, adaptable to the diversity of Indian landscapes, and integrative in its synthesis of stakeholder priorities and GIS-MCDA via the lens of SES. It provides a pathway from disparate site-specific studies with opaque decision-making processes to comparable, justifiable planning, enabling practitioners to demonstrate why a given PMLU was selected. Looking ahead, we aim to move from frameworks to action, piloting our people-centric approach across a representative set of Indian coal-mine sites to refine data requirements, validate weighting schemes, and test participatory tools such as PGIS and visioning workshops.

References

ACPET. (2025a). *Farmer Producer Organizations (FPOs): A Post-Mine Closure Transition Strategy*. Ashoka Centre for a People-Centric Energy Transition. https://www.acpet.ashoka.edu.in/pdf/ACPET_FPOs_Clean.pdf

ACPET. (2025b). *Mine Water Repurposing for Sustainable Livelihoods: Leveraging Water Bodies through Solar Lift Irrigation (SLI)*. Ashoka Centre for a People-Centric Energy Transition. https://www.acpet.ashoka.edu.in/pdf/ACPET_Solar_Pump_Irrigation_Clean.pdf

ACPET. (2025c). *Transforming Lives and Livelihoods in Coal Mine-Affected Communities: A Study of Livelihood and Clean Energy Interventions*. Ashoka centre for a People-Centric Energy Transition. https://www.acpet.ashoka.edu.in/pdf/Transforming_Life_and_Livelihood_of_Coal_Mine_Communities.pdf

Agrawal, K., Pathak, M., Jana, K., Unni, J., & Shukla, P. (2024). Just transition away from coal: Vulnerability analysis of coal districts in India. *Energy Research & Social Science*, *108*, 103355. https://doi.org/10.1016/j.erss.2023.103355

Aleksandrova, A. Y., & Timofeeva, S. S. (2021). Impact of mining of common minerals on the environment and public health. *IOP Conference Series: Earth and Environmental Science*, *848*(1), 012136. https://doi.org/10.1088/1755-1315/848/1/012136

Amaro, S. L., Barbosa, S., Ammerer, G., Bruno, A., Guimerà, J., Orfanoudakis, I., Ostręga, A., Mylona, E., Strydom, J., & Hitch, M. (2022). Multi-criteria decision analysis for evaluating transitional and post-mining options—An innovative perspective from the EIT ReviRIS project. *Sustainability*, *14*(4), 2292.

Arratia-Solar, A., Svobodova, K., Lèbre, É., & Owen, J. R. (2022). Conceptual framework to assist in the decision-making process when planning for post-mining land-uses. *The Extractive Industries and Society*, *10*, 101083. https://doi.org/10.1016/j.exis.2022.101083

Bainton, N., & Holcombe, S. (2018). A critical review of the social aspects of mine closure. *Resources Policy*, *59*, 468–478. https://doi.org/10.1016/j.resourpol.2018.08.020

Baker, J., Sheate, W. R., Phillips, P., & Eales, R. (2013). Ecosystem services in environmental assessment—Help or hindrance? *Environmental Impact Assessment Review*, *40*, 3–13.

Banerjee, S., Satyam, A., Sah, P., & Mary, A. (2024). *Sustainability Framework for Coal Mines—Instituting a Just Transition Plan for Mine Closure*. iFOREST - International Forum for Environment, Sustainability & Technology. https://iforest.global/research/sustainability-framework-for-coal-mines-request-download/

Beckett, C., & Keeling, A. (2019). Rethinking remediation: Mine reclamation, environmental justice, and relations of care. *Local Environment*, *24*(3), 216–230. https://doi.org/10.1080/13549839.2018.1557127

Bhushan, C., Banerjee, S., & Bissu, B. (2025). *Regional Just Transition Investment Plan: Chandrapur-Nagpur-Yavatmal*. iFOREST - International Forum for Environment, Sustainability & Technology. https://iforest.global/report/regional-just-transition-investment-plan-chandrapur-nagpur-yavatmal/

Bouchet, L., Thoms, M. C., & Parsons, M. (2022). Using Causal Loop Diagrams to Conceptualize Groundwater as a Social-Ecological System. *Frontiers in Environmental Science*, *10*. https://doi.org/10.3389/fenvs.2022.836206

Cao, Z., & Tang, J. (2025). A Framework for Post-Mining Area Restoration Based on Social-Ecological System Analysis. *Science, Engineering and Technology Proceedings*, *1*, 47–59. https://doi.org/10.71222/2qptd371

Chambers, R. (1994a). Participatory rural appraisal (PRA): Analysis of experience. *World Development*, *22*(9), 1253–1268. https://doi.org/10.1016/0305-750X(94)90003-5

Chambers, R. (1994b). The origins and practice of participatory rural appraisal. *World Development*, *22*(7), 953–969. https://doi.org/10.1016/0305-750X(94)90141-4

Coal Controller Organisation. (2025a). *Closure Beyond Compliance Embracing L.I.V.E.S. for a Sustainable Future*. Ministry of Coal, Government of India.

Coal Controller Organisation. (2025b). *RECLAIM: A Community Development Framework*. Ministry of Coal, Government of India. https://coal.gov.in/sites/default/files/2025-08/14-08-2025a-wn.pdf

Côte, C., Asmussen, P., & Gentle, C. (2022). *Dynamically transforming environmental assessment through a shared analytics framework: Bowen Basin case study*. University of Queensland. https://espace.library.uq.edu.au/view/UQ:1235185

Daily, G. C., & Matson, P. A. (2008). Ecosystem services: From theory to implementation. *Proceedings of the National Academy of Sciences*, *105*(28), 9455–9456. https://doi.org/10.1073/pnas.0804960105

Downing, A. S. (2022). CLD4SDGs: Integrated assessment of progress and impacts on Sustainable Development Goals using Causal Loop Diagrams. *MethodsX*, *9*, 101851. https://doi.org/10.1016/j.mex.2022.101851

Eastman, J. R., Toledano, J., Weigen, J., & Kyem, P. A. K. (1993). Participatory multi-objective decision-making in GIS. *Autocarto-Conference-. ASPRS American Society for Photogrammetry and Remote Sensing*, 33–42.

Egerer, S., Cotera, R. V., Celliers, L., & Costa, M. M. (2021). A leverage points analysis of a qualitative system dynamics model for climate change adaptation in agriculture. *Agricultural Systems*, *189*, 103052. https://doi.org/10.1016/j.agsy.2021.103052

Everingham, J., MacKenzie, S., Svobodova, K., & Witt, K. (2020). *Participatory processes, mine closure and social transitions*. Centre for Social Responsibility in Mining (CSRM), The University of Queensland, Australia.

Foran, T., Ackermann, F., & Barber, M. (2024). Values in post-mining regional transition: A political–economic regime approach, with insights from Australia. *The Extractive Industries and Society*, *20*, 101523. https://doi.org/10.1016/j.exis.2024.101523

Franz, C. (n.d.). *System Thinking & Causal Loop Diagrams—Sustainability Methods*. Retrieved October 2, 2025, from https://sustainabilitymethods.org/index.php/System_Thinking_%26_Causal_Loop_Diagrams

Giordano, R., Osann, A., Henao, E., López, M. L., Piqueras, J. G., Nikolaidis, N. P., Lilli, M., Coletta, V. R., & Pagano, A. (2025). Causal Loop Diagrams for bridging the gap between

Water-Energy-Food-Ecosystem Nexus thinking and Nexus doing: Evidence from two case studies. *Journal of Hydrology*, *650*, 132571. https://doi.org/10.1016/j.jhydrol.2024.132571

Grant, C., Loch, R., McCaffrey, N., Anstey, S., & Doley, D. (2016). *Mine Rehabilitation: Leading Practice Sustainable Development Program for the Mining Industry*. Department of Industry, Science and Resources, Australian Government. https://www.industry.gov.au/sites/default/files/2019-04/lpsdp-mine-rehabilitation-handbook-english.pdf

Greene, R., Devillers, R., Luther, J. E., & Eddy, B. G. (2011). GIS-Based Multiple-Criteria Decision Analysis. *Geography Compass*, *5*(6), 412–432. https://doi.org/10.1111/j.1749-8198.2011.00431.x

Hanf, F. S., Ament, F., Boettcher, M., Burgemeister, F., Gaslikova, L., Hoffmann, P., Knieling, J., Matthias, V., Meier, L., Pein, J., Poschlod, B., Quante, M., Ratzke, L., Rudolph, E., Scheffran, J., Schlünzen, K. H., Shokri, N., Sillmann, J., Vogelbacher, A., … Wickel, M. (2025). Towards a socio-ecological system understanding of urban flood risk and barriers to climate change adaptation using causal loop diagrams. *International Journal of Urban Sustainable Development*, *17*(1), 69–102. https://doi.org/10.1080/19463138.2025.2474399

Hanspach, J., Hartel, T., Milcu, A. I., Mikulcak, F., Dorresteijn, I., Loos, J., von Wehrden, H., Kuemmerle, T., Abson, D., Kovács-Hostyánszki, A., Báldi, A., & Fischer, J. (2014). A holistic approach to studying social-ecological systems and its application to southern Transylvania. *Ecology and Society*, *19*(4). https://www.jstor.org/stable/26269673

Haraldsson, H. V. (2004). *Introduction to system thinking and causal loop diagrams*. Department of chemical engineering, Lund University Lund, Sweden.

Herrero-Jáuregui, C., Arnaiz-Schmitz, C., Reyes, M. F., Telesnicki, M., Agramonte, I., Easdale, M. H., Schmitz, M. F., Aguiar, M., Gómez-Sal, A., & Montes, C. (2018). What do We Talk about When We Talk about Social-Ecological Systems? A Literature Review. *Sustainability*, *10*(8), 2950. https://doi.org/10.3390/su10082950

Hesketh, P., Zevallos, M., Chichakly, K., Fourie, A. B., Tibbett, M., & Boggs, G. (2024). *Development of an ecosystem model for post-mining land use with a systems dynamics approach* (pp. 365–374). Mine Closure 2024: 17th International Conference on Mine Closure, 2024 26-28 November 2024, Perth. Australian Centre for Geomechanics. https://doi.org/10.36487/ACG_repo/2415_26

Hilson, G., & Nayee, V. (2002). Environmental management system implementation in the mining industry: A key to achieving cleaner production. *International Journal of Mineral Processing*, *64*(1), 19–41. https://doi.org/10.1016/S0301-7516(01)00071-0

Holcombe, S., & Keenan, J. (2020). *Mining as a temporary land use scoping project: Transitions and repurposing*. Centre for Social Responsibility in Mining (CSRM), The University of Queensland, Australia.

Huang, L., Erskine, P., Parry, D., & Roddy, B. (2022). *Transforming engineering into ecological engineering for developing resilient ecosystems on mined landscapes*. 29–48. https://doi.org/10.36487/ACG_repo/2215_0.03

International Council on Mining and Metals. (2025, February 19). *Integrated Mine Closure: Good Practice Guide*. https://www.icmm.com/integrated-mine-closure

Kamboj, P., & Tongia, R. (2018). *Indian railways and coal: An unsustainable interdependency*.

Kansky, R., Riechers, M., & Fischer, J. (2025). Using causal loop diagrams to see the "big picture" and embrace complexity in human-wildlife coexistence governance. *Biological Conservation*, *308*, 111198. https://doi.org/10.1016/j.biocon.2025.111198

Khan, S. (2024, November 14). Restoring land is critical for India's economy and food security: Osama Faqeeha, UNCCD's COP16 advisor. *The Economic Times*. https://economictimes.indiatimes.com/small-biz/sustainability/restoring-land-is-critical-for-indias-economy-and-food-security-osama-faqeeha-unccds-cop16-advisor/articleshow/115285745.cms

Khan, U., Faheem, H., Jiang, Z., Wajid, M., Younas, M., & Zhang, B. (2021). Integrating a GIS-Based Multi-Influence Factors Model with Hydro-Geophysical Exploration for Groundwater Potential and Hydrogeological Assessment: A Case Study in the Karak Watershed, Northern Pakistan. *Water*, *13*(9), 1255. https://doi.org/10.3390/w13091255

Khanna, R., Malviya, T., & Goel, R. (2024). *Survey to Understand Impact of Coal Mine Closure and Transitioning Mining Communities to Sustainable Lives: Impact*

Assessment Report. Ashoka centre for a People-Centric Energy Transition, In Press. https://www.acpet.ashoka.edu.in/pdf/survey.pdf

Kivinen, S., Vartiainen, K., & Kumpula, T. (2018). People and Post-Mining Environments: PPGIS Mapping of Landscape Values, Knowledge Needs, and Future Perspectives in Northern Finland. *Land*, *7*(4), 151. https://doi.org/10.3390/land7040151

Limpitlaw, D., & Briel, A. (2014). Post-mining land use opportunities in developing countries—A review. *Journal of the Southern African Institute of Mining and Metallurgy*, *114*(11), 899–903.

Malczewski, J. (1999). *GIS and Multicriteria Decision Analysis*. John Wiley & Sons.

Malczewski, J. (2006). GIS-based multicriteria decision analysis: A survey of the literature. *International Journal of Geographical Information Science*, *20*(7), 703–726. https://doi.org/10.1080/13658810600661508

Masoudi, M., Centeri, C., Jakab, G., Nel, L., & Mojtahedi, M. (2021). GIS-Based Multi-Criteria and Multi-Objective Evaluation for Sustainable Land-Use Planning (Case Study: Qaleh Ganj County, Iran) "Landuse Planning Using MCE and Mola." *International Journal of Environmental Research*, *15*(3), 457–474. https://doi.org/10.1007/s41742-021-00326-0

Mborah, C., Bansah, K., & Boateng, M. (2015). Evaluating Alternate Post-Mining Land-Uses: A Review. *Environment and Pollution*, *5*(1), p14. https://doi.org/10.5539/ep.v5n1p14

Measham, T., Walker, J., Haslam McKenzie, F., Kirby, J., Williams, C., D'Urso, J., Littleboy, A., Samper, A., Rey, R., Maybee, B., Brereton, D., & Boggs, G. (2024). Beyond closure: A literature review and research agenda for post-mining transitions. *Resources Policy*, *90*, 104859. https://doi.org/10.1016/j.resourpol.2024.104859

Miller, F., Osbahr, H., Boyd, E., Thomalla, F., Bharwani, S., Ziervogel, G., Walker, B., Birkmann, J., van der Leeuw, S., Rockström, J., Hinkel, J., Downing, T., Folke, C., & Nelson, D. (2010). Resilience and Vulnerability: Complementary or Conflicting Concepts? *Ecology and Society*, *15*(3). https://www.jstor.org/stable/26268184

Ministry of Coal. (2025). *Guidelines for Preparation of Mining Plan and Mine Closure Plan for Coal and Lignite Blocks*. Ministry of Coal, Government of India. https://coal.gov.in/sites/default/files/2025-01/31-01-2025a-act.pdf

Mitra, J., Singh, A., & Victor. (2024). *Just Transition Framework for a Sustainable Future in India's Coal Mining Regions*. The Energy Resources Institute. https://teriin.org/sites/default/files/2024-02/Just%20Transition%20Framework%20for%20a%20Sustainable%20Future%20in%20India%E2%80%99s%20Coal%20Mining%20Regions.pdf

Murphy, D., Fromm, J., Bairstow, R., & Meunier, D. (2019). *A repurposing framework for alignment of regional development and mine closure*. 789–802. https://doi.org/10.36487/ACG_rep/1915_64_Murphy

Narayanasamy, N. (2009). *Participatory Rural Appraisal: Principles, Methods and Application*. SAGE Publications Ltd.

Nasir, M. J., Khan, S., Zahid, H., & Khan, A. (2018). Delineation of groundwater potential zones using GIS and multi influence factor (MIF) techniques: A study of district Swat, Khyber Pakhtunkhwa, Pakistan. *Environmental Earth Sciences*, *77*(10), 367. https://doi.org/10.1007/s12665-018-7522-3

O'Donnell, M. S., Whipple, A. L., Inman, R. D., Tarbox, B. C., Monroe, A. P., Robb, B. S., & Aldridge, C. L. (2024). Remote sensing for monitoring mine lands and recovery efforts. In *Circular* (No. 1525). U.S. Geological Survey. https://doi.org/10.3133/cir1525

Ostrom, E. (2009). A General Framework for Analyzing Sustainability of Social-Ecological Systems. *Science*, *325*(5939), 419–422. https://doi.org/10.1126/science.1172133

Padma, P., Ganesh, L. S., & Rajendran, C. (2008). A study on the ISO 14000 certification and organizational performance of Indian manufacturing firms. *Benchmarking: An International Journal*, *15*(1), 73–100.

Pagouni, C., Pavloudakis, F., Kapageridis, I., & Yiannakou, A. (2024). Transitional and Post-Mining Land Uses: A Global Review of Regulatory Frameworks, Decision-Making Criteria, and Methods. *Land*, *13*(7), 1051. https://doi.org/10.3390/land13071051

Pearman, G. (2009). *101 Things to Do with a Hole in the Ground*. Post-Mining Alliance.

Perdeli Demirkan, C., Smith, N. M., & Duzgun, S. (2022). A Quantitative Sustainability Assessment for Mine Closure and Repurposing Alternatives in Colorado, USA. *Resources*, *11*(7), 66. https://doi.org/10.3390/resources11070066

Proag, V. (2014). The concept of vulnerability and resilience. *Procedia Economics and Finance*, *18*, 369–376.

Rahnama, M. R. (2023). Using Multi-Objective Land Allocation Model to Simulate Urban Growth: The Case of Sarakhs Border City in Iran. In *Contemporary Issues in Land Use Planning*. IntechOpen. https://doi.org/10.5772/intechopen.107159

Rane, N. L., Günen, M. A., Mallick, S. K., Rane, J., Pande, C. B., Giduturi, M., Bhutto, J. K., Yadav, K. K., Tolche, A. D., & Alreshidi, M. A. (2024). GIS-based multi-influencing factor (MIF) application for optimal site selection of solar photovoltaic power plants in Nashik, India. *Environmental Sciences Europe*, *36*(1), 5. https://doi.org/10.1186/s12302-023-00832-2

Rane, N. L., & Jayaraj, G. K. (2022). Comparison of multi-influence factor, weight of evidence and frequency ratio techniques to evaluate groundwater potential zones of basaltic aquifer systems. *Environment, Development and Sustainability*, *24*(2), 2315–2344. https://doi.org/10.1007/s10668-021-01535-5

Reeves, J. M., Baumgartl, T., Morgan, D., Reimers, V., & Green, M. (2022). Community capacity to envisage a post-mine future: Rehabilitation options for Latrobe Valley brown coal mines. *Mine Closure 2022: Proceedings of the 15th International Conference on Mine Closure*, 173–186. https://papers.acg.uwa.edu.au/p/2215_09_Reeves/

Rodon, T., Thériault, S., Keeling, A., Bouard, S., & Taylor, A. (2025). *Mining and Indigenous Livelihoods: Rights, revenues, and resistance*. Taylor & Francis.

Rolfe, J., Everingham, J.-A., Akbar, D., Kinnear, S., & Lechner, A. (2018). *Using workshop processes to generate stakeholder agreement about transferring post-mine land to grazing in Central Queensland* (No. C25032: Report 5). ACARP.

Ronyastra, I. M., Saw, L. H., & Low, F. S. (2023). A review of methods for integrating risk management and multicriteria decision analysis in financial feasibility for post-coal-mining land usage selection. *Resources Policy*, *86*, 104260. https://doi.org/10.1016/j.resourpol.2023.104260

Rosa, J. C. S., Sánchez, L. E., & Morrison-Saunders, A. (2018). Getting to 'agreed' post-mining land use – an ecosystem services approach. *Impact Assessment and Project Appraisal*, *36*(3), 220–229. https://doi.org/10.1080/14615517.2018.1445175

Saaty, T. L. (2006). The Analytic Network Process – Dependence and Feedback in Decision-Making: Theory and Validation Examples. In *Business Applications and Computational Intelligence* (pp. 360–387). IGI Global Scientific Publishing. https://doi.org/10.4018/978-1-59140-702-7.ch018

Saaty, T. L. (2013). Analytic hierarchy process. In *Encyclopedia of operations research and management science* (pp. 52–64). Springer.

Schneider, D., Haskett, W., & Thrift, A. (2023). *Using decision science to build trust in mine closure decisions*. https://doi.org/10.14288/1.0437489

Simpson, G. B., Ferguson, K., Slingerland, N., Jewitt, G. P. W., Alekseenko, A. V., Simpson, Z. Z., Ennis-John, J., Hattingh, R., & Stock, K. (2025). Integrating the sustainable development goals into post-mining land use selection. *Nature Scientific Reports*, *15*(1), 31974. https://doi.org/10.1038/s41598-025-15980-z

Sincovich, A., Gregory, T., Wilson, A., & Brinkman, S. (2018). The social impacts of mining on local communities in Australia. *Rural Society*, *27*(1), 18–34. https://doi.org/10.1080/10371656.2018.1443725

Singh, L., Saravanan, S., Jennifer, J. J., & Abijith, D. (2021). Application of multi-influence factor (MIF) technique for the identification of suitable sites for urban settlement in Tiruchirappalli City, Tamil Nadu, India. *Asia-Pacific Journal of Regional Science*, *5*(3), 797–823. https://doi.org/10.1007/s41685-021-00194-8

Sitorus, F., Cilliers, J. J., & Brito-Parada, P. R. (2019). Multi-criteria decision making for the choice problem in mining and mineral processing: Applications and trends. *Expert Systems with Applications*, *121*, 393–417. https://doi.org/10.1016/j.eswa.2018.12.001

Stacey, J., Naude, A., Hermanus, M., & Frankel, P. (2010). The socio-economic aspects of mine closure and sustainable development: Literature overview and lessons for the socio-economic aspects of closure - Report 1. *Journal of the Southern African Institute of Mining and Metallurgy*, *110*(7), 379–394.

Stevens, R., & Brock, D. (2021). Mine closure challenges for government and industry. *Intergovernmental Forum on Mining*. https://www.igfmining.org/mine-closure-challenges-government-industry/

Svobodova, K., Owen, J. R., & Harris, J. (2021). The global energy transition and place attachment in coal mining communities: Implications for heavily industrialized landscapes. *Energy Research & Social Science*, *71*, 101831. https://doi.org/10.1016/j.erss.2020.101831

Unger, C. J., Everingham, J.-A., & Bond, C. J. (2020). Transition or transformation: Shifting priorities and stakeholders in Australian mined land rehabilitation and closure. *Australasian Journal of Environmental Management*, *27*(1), 84–113. https://doi.org/10.1080/14486563.2020.1719440

Valencia, R. (2020). A Group Model Building approach for climate change adaptation of agricultural systems in Northeast Lower Saxony. *International Congress on Environmental Modelling and Software*. https://scholarsarchive.byu.edu/iemssconference/2020/Stream-A/29

Vázquez-González, C., Ávila-Foucat, V. S., Ortiz-Lozano, L., Moreno-Casasola, P., & Granados-Barba, A. (2021). Analytical framework for assessing the social-ecological system trajectory considering the resilience-vulnerability dynamic interaction in the context of disasters. *International Journal of Disaster Risk Reduction*, *59*, 102232.

Vivoda, V., Kemp, D., & Owen, J. (2019). Regulating the social aspects of mine closure in three Australian states. *Journal of Energy & Natural Resources Law*, *37*(4), 405–424. https://doi.org/10.1080/02646811.2019.1608030

Wang, Y., Gong, J., Yang, Z., & Zhu, Y. (2025). Social-ecological system research in a changing world: State of the art and future challenges. *Journal of Cleaner Production*, *489*, 144725. https://doi.org/10.1016/j.jclepro.2025.144725

Worden, S., Svobodova, K., Côte, C., & Bolz, P. (2024). Regional post-mining land use assessment: An interdisciplinary and multi-stakeholder approach. *Resources Policy*, *89*, 104680. https://doi.org/10.1016/j.resourpol.2024.104680

Annex A: Mine Repurposing Case Studies

India

Recreation and Tourism

Several coal and lignite mine sites are being repurposed into eco-parks, lakefronts, and recreational destinations to promote community engagement and local economic development. These initiatives transform abandoned or degraded mine landscapes such as overburden dumps and water-filled voids into sustainable tourism assets, enhancing environmental aesthetics while generating employment for local populations.[27]

Agriculture and Livelihoods

Post-mining landscapes are being restored to productive use through agriculture, horticulture, pisciculture, and animal husbandry. Such initiatives, implemented by Coal India subsidiaries and state mining corporations, aim to revive land productivity, enhance food security, and provide alternative, sustainable livelihoods for communities previously dependent on mining.[28]

Skill Development, Enterprise and Socio-Economic Development

Skill development and enterprise-promotion programmes in coal-bearing districts of India are central to enabling a "just transition." These initiatives equip local communities with new skills, encourage entrepreneurship, and support small-scale industries, ensuring that economic diversification and social inclusion accompany mine closure and decline in coal activity.[29]

---

[27] Ministry of Coal, Government of India. (2022). *Best Practices in Mine Closure and Reclamation in India*. New Delhi: Ministry of Coal.
[28] Central Mine Planning and Design Institute (CMPDI). (2019). *Post-Mining Land Use in India – A Compendium of Good Practices.* Ranchi: CMPDI
[29] NITI Aayog. (2021). *Framework for Just Transition in India's Coal Regions.* New Delhi: NITI Aayog

Water Management and Community Utility

Mine water, a by-product of dewatering operations, is increasingly being treated and reused across India for irrigation, domestic supply, and industrial use. This approach, led by Coal India Limited and supported by CMPDI, addresses water scarcity in coal-bearing regions and converts mine discharge into a valuable community resource.[30]

Ecological Restoration

Ecological restoration efforts in Indian mining areas focus on afforestation, topsoil management, and biodiversity conservation to rehabilitate mined-out lands. Programmes under the Ministry of Coal and MoEFCC promote large-scale green cover development, including the adoption of dense plantation techniques such as the Miyawaki method, to restore ecosystem functions and enhance local climate resilience.[31]

[30] Central Mine Planning and Design Institute (CMPDI). (2022). *Compilation on Mine Water Utilization Projects in Coal India Areas.* Ranchi: CMPDI

[31] Ministry of Environment, Forest and Climate Change (MoEFCC). (2020). *Guidelines on Environmental Restoration of Mined-Out Areas.* New Delhi: MoEFCC.

Select Indian Case Studies

State	Case Study	Commissioning Company	Domain	Key Highlights
Chhattisgarh	Bishrampur OC Mine (Kenapara)	South Eastern Coalfields Limited (SECL)	Recreation & Tourism	Abandoned Quarry No. 6 (10.5 ha) in Surajpur developed as an eco-tourism site with boating, floating raft, and restaurant; attracts 100+ visitors daily. [32]
			Agriculture & Livelihoods	Quarry waterbody developed for pisciculture managed by Mahamaya Fisheries Society; ~24,000 kg annual fish yield.
			Skill Development & Enterprise	Boating is managed by Shiv Shakti Mahila Gram Sanghathan (women's SHG collective); empowers 186 households.[33]
Gujarat	All Lignite Mines of GMDC (Backfilled	Gujarat Mineral Development Corporation Ltd.	Ecological Restoration	1,300 ha afforested with ~30 lakh trees; serves as a major

[32] Kenapara Site Manual, accessed via Scribd, https://www.scribd.com/document/650525518/Kenapara-Site-Manual.
[33] *Repurposing Options for Coal Mines in India*, accessed via Energy Forum, 24–25, https://energyforum.in/fileadmin/india/media_elements/publications/Repurposing_Options_for_Coal_Mines_in_India/Repurposing_Coal_Mines.pdf.

	Area/OB Dumps)	(GMDC)		carbon sink.[34]
			Agriculture & Livelihoods	At Amod Lignite Mine, backfilled areas used for Sunn Hemp cultivation support rural livelihoods.[35]
Jharkhand	Amalgamated Keshalpur–West Mudidih (AKWMC)	Bharat Coking Coal Limited (BCCL)	Recreation & Tourism	Overburden dump repurposed into an eco-park with amphitheatre, outdoor gym, medicinal garden, pond, and food kiosks; ~20,000 visitors annually.
	Central Saunda Pisciculture Project (Barkasayal Area)	Central Coalfields Limited (CCL)	Agriculture & Livelihoods	40 fish cages with Tilapia species; benefits ~250 villagers; enhances fish production and employment.[36]
	Gidi A Pisciculture	Central Coalfields Limited (CCL)	Agriculture & Livelihoods	28 ha waterbody; 22 fish cages; 0.72

[34] CSRBOX, "Gujarat Mineral Development Corporation — Tree Guard Distribution, Gujarat," accessed via CSRBOX, https://csrbox.org/India_CSR_Project_Gujarat-Mineral-Development-Corporation-Limited-Tree-Guard-Distribution-Gujarat_6212. Google Drive file, accessed via Drive, https://drive.google.com/file/d/1_Q-Y6GoytsqXzo_hRgQopTEY91SQhGU4/view.

[35] GMDC (Facebook), "GMDC Is Committed to Sustainable Growth … Mine-Closure Plan," video, accessed via Facebook, https://www.facebook.com/100077082217367/videos/gmdc-is-committed-to-sustainablegrowth-our-mine-closure-plan-strives-to-develop-/209298638553189/.

[36] Press Information Bureau, "CCL's Pisciculture Projects …" (PIB Press Release), accessed via PIB, https://www.pib.gov.in/PressReleasePage.aspx?PRID=2065260#:~:text=CCL's%20pisciculture%20projects%20have%20been

	Project (Argada Area)			tonnes first-year yield; benefits local villages; proposed Ramsar wetland.
	Govardhan Eco-Park (Bera, Bastacolla Area)	Bharat Coking Coal Limited (BCCL)	Recreation & Tourism	7.65 ha eco-park with fountains, gardens, prayer hall, cafeteria, and water body; showcases integrated social and environmental benefits.[37]
	Karkatta A & Karkatta C Pisciculture Projects (NK Area)	Central Coalfields Limited (CCL)	Agriculture & Livelihoods	65 cages over 6.3 ha; combined output ~1,000 tonnes annually; supports household incomes and nutrition.[38]
	Pachhwara North Coal Mine (Pakur) West Bengal Power Development Corporation Ltd. (WBPDCL)		Agriculture & Livelihoods	The 68.4-acre site was developed for dairy, goatery, poultry, aquaculture, and vegetable cultivation; 300 jobs; 2,000 people benefited.[39]

[37] Bharat Coking Coal Limited, *Eco-Tourism* (pdf), accessed via BCCL, https://www.bcclweb.in/files/2022/08/Eco-tourism.pdf.
YouTube video, "A38yFgRybxQ," accessed via YouTube, https://youtu.be/A38yFgRybxQ?si=DD4UxMXIr15RdJq7.

[38] Press Information Bureau, "CCL's Pisciculture Projects …" (PIB Press Release), accessed via PIB, https://www.pib.gov.in/PressReleasePage.aspx?PRID=2065260#:~:text=CCL's%20pisciculture%20projects%20have%20been

[39] YouTube video "JDDzmmb0qao," accessed via YouTube, https://youtu.be/JDDzmmb0qao?si=UTeCHSdWN7HiX3yf.

			Skill Development & Enterprise	₹140 lakh budget for SHG training in Sal Pattal making, bamboo craft, and JFM capacity building.[40]
	Religara Pisciculture Project (Argada Area)	Central Coalfields Limited (CCL)	Agriculture & Livelihoods	9.71 ha area; 20 fish cages; 9.6 tonnes annual fish yield; benefits ~100 residents through income and nutrition[41]
	West Bokaro Coal Mine	Tata Steel Limited (TSL)	Recreation & Tourism	Overburden dump converted to multiple parks (JN Tata, Sir Dorabji Tata, Naxtra); ~200,000 visitors/year; 360 jobs.
			Water Management & Community Utility	7 million KL reservoir for groundwater recharge; drinking water supplies to seven villages.
Madhya Pradesh	Ananya Vatika (Rajnagar OCP, Hasdeo Area)	South Eastern Coalfields Limited (SECL)	Ecological Restoration	Reclaimed area converted into wetland and biodiversity garden;

[40] Google Drive file, accessed via Drive, https://drive.google.com/file/d/1_Q-Y6GoytsqXzo_hRgQopTEY91SQhGU4/view.

[41] Press Information Bureau, "CCL's Pisciculture Projects ..." (PIB Press Release), accessed via PIB, https://www.pib.gov.in/PressReleasePage.aspx?PRID=2065260#:~:text=CCL's%20pisciculture%20projects%20have%20been

				showcases ecological restoration on mined land.[42]
			Water Management & Community Utility	Mine water sustains wetlands and supplies clean water to nearby villages.[43]
	Mudwani Dam Eco-Park	Northern Coalfields Limited (NCL)	Recreation & Tourism	Eco-park with landscaped water bodies and green pathways; improve regional tourism and community well-being.[44]
	Nigahi Mine (Singrauli)	Northern Coalfields Limited (NCL)	Ecological Restoration	Bamboo plantations, rainwater pits, percolation wells; drip irrigation for slope stability and biodiversity.[45]

[42] Comptroller and Auditor General of India, *Report No. 12 of 2019: Assessment of Environmental Impact due to Mining Activities and its Mitigation in Coal India Limited and its Subsidiaries*, accessed via CAG, https://cag.gov.in/uploads/download_audit_report/2019/Report_No_12_of_2019_Assessment_of_Environmental_Impact_due_to_Mining_Activities_and_its_Mitigation_in_Coal_India_Limited_and_its_Subsidiaries.pdf.
Coal India (Facebook), "Ananya Vatika — SECL," video, accessed via Facebook, https://www.facebook.com/coalindiaHQ/videos/ananya-vatika-secl/1463189390424779/.
[43] Ministry of Coal (X / Twitter), post, "1815345538688311331," https://x.com/CoalMinistry/status/1815345538688311331.
[44] "Coal-Mine Tourism: Abandoned Mines Now Eco Parks," *The India Review*, accessed via TheIndiaReview, https://www.theindiareview.com/news/enviroment-news/coal-mine-tourism-abandoned-mines-now-eco-parks/
[45] Ministry of Coal, "PIB2101294" (coal.nic.in), accessed via PIB / Coal, https://coal.nic.in/sites/default/files/2025-02/PIB2101294.pdf.

			Recreation & Tourism	Developed eco-park and wetland for recreation and education; model for large-scale restoration.
Maharashtra	Patansaongi UG Mine (Saoner Area)	Western Coalfields Limited (WCL)	Water Management & Community Utility	Mine water treated via RO & UV systems; branded “COAL NEER” drinking water; supplies ~1 lakh beneficiaries[46]
	Saoner UG Mine & Gondegaon OC Mine	Western Coalfields Limited (WCL)	Recreation & Tourism	Mahatma Gandhi Eco-Park with a mine museum, toy train, and artificial mine tunnel promotes mining heritage.[47]
Rajasthan	Kapurdi and Jalipa Lignite Mines (Barmer)	Barmer Lignite Mining Company Ltd. (BLMCL)	Agriculture & Livelihoods	Integrated farming with Kharif crops and livestock; 15% productivity rise after training 1,170 farmers.
			Skill Development & Enterprise	Training for 600 women in handicrafts and embroidery; ₹30 lakh earnings via

[46] Coal (Govt of India), “Success Story — MWU,” accessed via coal.gov.in, https://coal.gov.in/sites/default/files/2019-09/success-story-3-mwu.pdf.
[47] Western Coalfields Limited, “Home — Four Block,” accessed via WesternCoal, https://westerncoal.in/index1.php/Homefourblock/1.

				SHGs.[48]
Tamil Nadu	Neyveli Mine-I, IA & II Opencast Project	Neyveli Lignite Corporation India Ltd. (NLCIL)	Ecological Restoration	Artificial lakes for recharge, wetlands, and agroforestry; enhances resilience[49]
			Recreation & Tourism	Reclaimed sites developed into eco-parks with biodiversity features.
			Renewable Energy & Storage	Floating & land-based solar PV plants; model for integrating renewables[50]
			Agriculture & Livelihoods	Brinjal, okra, and paddy cultivation on reclaimed land; greenhouses support livelihoods.[51]

[48] Google Drive file, accessed via Drive, https://drive.google.com/file/d/1_Q-Y6GoytsqXzo_hRgQopTEY91SQhGU4/view.
[49] Environment Clearance, "Download Pdf File," accessed via environmentclearance.nic.in, https://environmentclearance.nic.in/DownloadPfdFile.aspx?FileName=mjOt5PHtquVGd+G34wCV4pbuzKNUJriVgNTsjrH/pCrWnmFd8g3HmP8Owufuc2xt47i7REgOSM+AHckIFXl8Or7OwIQK3JstI29eJIVCvSmA7vpJCEClELLoeIosMXnF&FilePath=93ZZBm8LWEXfg+HAlQix2fE2t8z/pgnoBhDlYdZCxzXmG8GlihX6H9UP1HygCn3pCkAF2zPFXFQNqA4krKa1Aw==.
[50] Coal Controller, "Photo Gallery — Repurposing Mine Closure," accessed via coalcontroller.gov.in, https://coalcontroller.gov.in/photo-gallery/repurposing-mine-closure.

[51] Coal Controller, "Photo Gallery — Repurposing Mine Closure," accessed via coalcontroller.gov.in, https://coalcontroller.gov.in/photo-gallery/repurposing-mine-closure. Environment Clearance, "Download Pdf File," accessed via environmentclearance.nic.in, https://environmentclearance.nic.in/DownloadPfdFile.aspx?FileName=mjOt5PHtquVGd+G34wCV4pbuzKNUJriVgNTsjrH/pCrWnmFd8g3HmP8Owufuc2xt47i7REgOSM+AHckIFXl8Or7

			Water Management & Community Utility	Treated mine water supplies 300 lakh KL/year to 40 villages & Chennai Metro (~3 lakh people).[52]
Telangana	Coal Tourism Development in GDK-7 LEP	Singareni Collieries Company Limited (SCCL)	Recreation & Tourism	Underground tourism parks using chairlift systems promote mining heritage and public engagement.[53]

International

Water Management

Water management refers to the process of planning, developing, distributing, and optimizing the use of water resources in a sustainable manner, ensuring adequate supply for human, agricultural, and environmental needs.[54]

Ecological Restoration

Ecological restoration is the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed, to reestablish its ecological integrity,

OwIQK3JstI29eJIVCvSmA7vpJCEClELLoeIosMXnF&FilePath=93ZZBm8LWEXfg+HAlQix2fE2t8z/pgnoBhDlYdZCxzXmG8GlihX6H9UP1HygCn3pCkAF2zPFXFQNqA4krKa1Aw==.

[52] Ministry of Coal, "PIB2101294" (coal.nic.in), accessed via PIB / Coal, https://coal.nic.in/sites/default/files/2025-02/PIB2101294.pdf.

[53] TSRTC to Promote Underground Coal Mines Tourism," *Deccan Chronicle*, December 27, 2022, https://www.deccanchronicle.com/nation/in-other-news/271222/tsrtc-to-promote-underground-coal-mines-tourism.html.

[54] UN ESCWA. (n.d.). *Water management*. United Nations Economic and Social Commission for Western Asia. https://www.unescwa.org/sd-glossary/water-management

biodiversity, and resilience.[55]

Enterprise Development

Enterprise development involves promoting and supporting the creation and growth of businesses to generate income, employment, and innovation, contributing to local and national economic growth.[56]

Recreation & Tourism

Recreation and tourism encompass leisure activities and travel undertaken for enjoyment, cultural experience, or education, often contributing to community revitalisation and local economies.[57]

Renewable Energy & Storage

Renewable energy refers to energy derived from natural sources that are replenished at a faster rate than they are consumed, such as sunlight, wind, and water. Energy storage allows excess renewable energy to be saved for later use.[58]

Heritage Conservation

Heritage conservation involves identifying, protecting, and managing cultural and natural heritage to preserve its value for present and future generations.[59]

---

[55] Society for Ecological Restoration (SER). (2021). *What is ecological restoration?* https://ser-rrc.org/what-is-ecological-restoration/

[56] UNDP. (2017). *Enterprise development and entrepreneurship promotion.* United Nations Development Programme. https://www.undp.org/publications

[57] World Tourism Organization (UNWTO). (2022). *Tourism definitions.* https://www.unwto.org/glossary-tourism-terms

[58] International Renewable Energy Agency (IRENA). (2021). *Renewable energy and energy storage.* https://www.irena.org

[59] UNESCO. (2019). *Operational Guidelines for the Implementation of the World Heritage Convention.* https://whc.unesco.org/en/guidelines/

Education & Research

Education and research focus on the systematic transmission of knowledge and the generation of new insights through investigation, experimentation, and academic learning.[60]

Community Development

Community development is a process where community members come together to take collective action and generate solutions to common problems, fostering empowerment and resilience.[61]

Employment Generation

Employment generation involves creating sustainable job opportunities, particularly in emerging or transitioning economies, to enhance livelihoods and reduce poverty.[62]

Urban Renewal

Urban renewal is the process of redeveloping deteriorated urban areas through planning, investment, and modernisation to improve living conditions and economic vitality.[63]

Community Utility

Community utilities refer to local infrastructure and services such as power, water, and sanitation systems, developed or managed for the collective benefit of a community.[64]

---

[60] UNESCO Institute for Statistics. (2012). *International Standard Classification of Education (ISCED).* https://uis.unesco.org

[61] UN Habitat. (2020). *Community development and local governance.* https://unhabitat.org

[62] International Labour Organization (ILO). (2020). *Employment and decent work.* https://www.ilo.org

[63] UN-Habitat. (2019). *Urban regeneration.* https://unhabitat.org

[64] World Bank. (2022). *Community infrastructure and services.* https://www.worldbank.org

Education & Skilling

Education and skilling focus on providing individuals with both foundational learning and practical vocational training to increase employability and productivity.[65]

Select Global Case Studies

Country	Case Study	Implementing Organisation(s)	Project Type	Developmental Domains Covered	Key Highlights
Australia	Hazelwood Mine Transformation (Victoria)	ENGIE Australia; State Govt. Victoria	Lake rehabilitation and renewable energy hub	Water Management; Renewable Energy & Storage	Conversion of mine void into lake and floating solar project; long-term ecological monitoring[66]
Canada	SunMine Solar Park (Kimberley, BC)	City of Kimberley; Teck Resources Ltd.; EcoSmart Foundation	Grid-connected solar PV (1.05 MW) on reclaimed mine	Renewable Energy & Storage; Community Utility; Enterprise Development	Canada's first municipal solar project on reclaimed mining land; sells power to BC Hydro; creates green-energy jobs; exemplifies municipal–

[65] OECD. (2021). *Skills for jobs: Education and training policies.* https://www.oecd.org
[66] Australian Department of Industry, Science and Resources (2023); Queensland Department of Environment and Science (2022).

					industry collaboration.[67]
Chile	Chuquicamata Mine Closure Transformation	Codelco Chile; Ministry of Mining	Copper mine rehabilitation → industrial heritage and solar hub	Heritage Conservation; Renewable Energy & Storage	Converts old mine facilities for solar testing and heritage tours; solar R&D initiatives[68]
China	Taiyuan Botanical Garden (Shanxi)	Shanxi Provincial Govt.; DMAA Architects	Botanical garden and research centre on reclaimed mining land	Recreation & Tourism; Education & Research; Ecological Restoration	Integrates domed greenhouses and wetlands on former mining land; enhances urban biodiversity; offers education and recreation; symbol of eco-urban regeneration[69]
	Tangshan Quarry Park (Hebei)	Tangshan City Govt.; Shanshui Landscape Design	Quarry-to-urban-park conversion	Recreation & Tourism; Ecological Restoration; Urban Renewal	The 40-hectare quarry turned into an ecological park with lakes, restored cliffs, and cultural spaces; strengthens city resilience and aesthetic value.[70]

[67] EcoSmart Foundation (2015); Teck Resources Ltd. (2015)
[68] Carbajales & González (2021)
[69] DMAA Architects (2020).
[70] Shanshui Landscape Design (2019

Colombia	El Cerrejón Post-Mining Sustainability Program	Cerrejón Ltd.; WWF Colombia	Ecological and community restoration of coal region	Ecological Restoration; Community Development	Land reforestation (20,000 ha); community agriculture and training initiatives.[71]
Czech Republic	František Mine Industrial Park (Horní Suchá)	Horní Suchá Municipality; CzechInvest; Local Enterprises	Industrial-park redevelopment on decommissioned coal min	Industrial Redevelopment; Employment Generation; Infrastructure Reuse	14-hectare site upgraded with modern utilities and 43,000 m² of facilities; now hosts 25 companies & 300 employees; showcases Central Europe's post-mining industrial transition[72]
Germany	Lusatian Lakeland (Lausitzer Seenland)	Lausitzer SeenLand GmbH; Saxony & Brandenburg Regional Authorities	Flood-and-repurpose lignite pits into interconnected lakes and tourism network	Recreation & Tourism; Water Management; Ecological Restoration	Europe's largest artificial-lake project; >20 open-cast pits (≈14,000 ha) flooded and connected; promotes tourism, eco-enterprises, and biodiversity recovery[73]

[71] National Mining Agency of Colombia (2023)
[72] Horní Suchá Municipality (2021)
[73] Lausitzer SeenLand GmbH (2022); Kivinen (2017)

	Cottbus Ostsee Floating PV	LEAG; EP New Energies GmbH; EPH Holding	Floating solar photovoltaic system (21–29 MWp)	Renewable Energy & Storage; Water Management; Enterprise Development	Former lignite mine converted to a lake hosting Germany's largest floating solar array; produces clean energy, prevents evaporation loss, supports regional green jobs.[74]
	Rewilding the Ruhr (wildE Project)	Research Consortia & NGOs (Wageningen University; Local Municipalities)	Ecological rewilding & afforestation of former coal regions	Ecological Restoration; Recreation & Tourism; Community Enterprise	Converts spoil heaps and industrial corridors into forest parks and biodiversity zones; promotes eco-tourism and environmental education; model for post-industrial rewilding.[75]
	Cottbus Ostsee Floating Solar Project	EP New Energies GmbH; LEAG; Lausitz Energy Park	Floating solar photovoltaic installation on former lignite mine lake	Renewable Energy & Storage; Water Management; Enterprise Development	Former opencast lignite mine transformed into a 1,900-hectare lake hosting one of Europe's largest floating

[74] *EP New Energies GmbH (2023); LEAG (2023)*
[75] Wageningen University (2021)

					PV arrays (29 MWp); supports regional green jobs and clean-energy generation; contributes to Lusatia's post-coal transition.[76]
Greece	Ptolemaida Energy Transition Park (West Macedonia)	PPC Renewables; Hellenic Ministry of Energy	Solar and industrial hub on former lignite mine	Renewable Energy & Storage; Employment Generation; Community Development	200 MW solar farm on reclaimed mine; anchors regional "Just Transition" plan.[77]
	Western Macedonia Data Centre & Technology Hubs Program	Hellenic Republic Asset Development Fund; PPC; Microsoft Greece	ICT and data-infrastructure redevelopment on former lignite lands	Industrial Redevelopment; Employment Generation; Digital Infrastructure	€5.8 billion program to repurpose mining terrain for data centres & logistics parks; supports regional economic diversification and digital innovation.[78]
Indonesia	Samarinda Mine Rehabilitatio	Ministry of Energy; Adaro	Agroforestry and fish	Ecological Restoration; Community	Combines reforestation with aquaculture

[76] EP New Energies GmbH (2023); LEAG (2023).
[77] Greek Centre for Research & Technology Hellas (CERTH) (2022)
[78] Hellenic Republic Asset Development Fund (2023).

	n (East Kalimantan	Energy Indonesia	farming on coal voids	Development; Employment Generation	cooperatives; improves livelihoods.[79]
Japan	Kushiro Mine Renewable District (Hokkaido)	City of Kushiro; JOGMEC	Geothermal and biomass reuse of coal infrastructure	Renewable Energy & Storage; Enterprise Development	Develops low-carbon district heating; preserves coal heritage; creates green employment.[80]
Jordan	Ma’an Solar Cluster on Phosphate Mine Lands	Ministry of Energy; Masdar UAE	Solar farm development on desert mine lands	Renewable Energy & Storage; Employment Generation	Converts idle mining area into Ma’an Renewable Energy Park (160 MW); training local youth.[81]
Namibia	Tsumeb Mine Rehabilitatio n and Solar Farm	Dundee Precious Metals; NamPower	Solar energy and revegetation of base-metal mine	Renewable Energy & Storage; Ecological Restoration	Combines mine-waste rehab with 10 MW solar facility; supports local grid and habitat restoration.[82]
Netherlands	Heerlen Minewater Project	Municipality of Heerlen; Mijnwater B.V.; Research Partners	Mine-water geothermal heating & cooling network	Water Management; Ecological Restoration;	Reuses flooded coal-mine workings for district heating and cooling;

[79] Centre for Sustainable Resource Development, Indonesia (2023).

[80] Japan Coal Energy Center (JCOAL) (2021).
[81] Jordan Phosphate Mines Company (2022)
[82] Chamber of Mines Namibia (2022)

			(Minewater 2.0)	Enterprise Development	supplies renewable thermal energy to local homes; reduces CO_2 emissions by over 50%; generates local green-energy employment.[83]
Poland	Bełchatów Mine Solar and Hydrogen Hub	PGE Polska Grupa Energetyczna; Orlen	Renewable energy conversion of Europe's largest lignite mine	Renewable Energy & Storage; Enterprise Development	Plans for 2 GW solar & wind capacity; hydrogen production pilot; regional energy transition.[84]
Slovenia	Zasavje Solar Power Plant	Slovenian Energy Agency; HSE Group; Zasavje Municipality	Solar farm on former coal-power-plant site	Renewable Energy & Storage; Carbon Reduction; Industrial Reuse	Largest solar facility in Slovenia, built on reclaimed brownfield; supports national energy-transition goals and local job creation.[85]
South Africa	Highveld Industrial Park	Arnot OpCo; IDC South Africa	Industrial and logistics hub on coal land	Enterprise Development; Employment Generation	1,200 jobs created; repurposed power plant

[83] Heerlen, Municipality & Mijnwater B.V. (2019). *Minewater 2.0 – Sustainable Geothermal District Energy*. Municipality of Heerlen Publication.
[84] World Bank (2023)
[85] HSE Group (2024)

	(Mpumalang a)				infrastructure for manufacturing[86]
United Kingdom	Eden Project North (Cornwall)	Eden Trust; UK Govt. Levelling Up Fund	Regeneration of clay mine into eco-tourism destination	Recreation & Tourism; Education & Research; Enterprise Development	Immersive environmental park creating 400+ green jobs; focus on climate education[87]
USA	Pittsburgh Botanic Garden (Pennsylvani a)	Pittsburgh Botanic Garden Foundation; EPA; Local Conservation Groups	Botanical garden with AMD remediation	Ecological Restoration; Water Management; Recreation & Tourism	Restores 460 acres of mine-scarred land using limestone wetlands and reforestation; showcases AMD treatment success; promotes environmental education.[88]
	Portal 31 Undergroun d Mine Tour (Kentucky)	Portal 31 Heritage Museum; Kentucky Tourism Board	Underground heritage tourism and museum	Recreation & Tourism; Heritage Conservation; Education & Community Development	Converts an old coal mine into an interactive museum; preserves industrial history; creates tourism-based employment in a

[86] African Development Bank (2022); Energy Research Centre, University of Cape Town (2023
[87] World Bank (2023)
[88] Pittsburgh Botanic Garden Foundation (2020).

					post-mining town.[89]
	West Suscon Reclamation / CenterPoint Trade Park (Pennsylvania)	PA DEP; Mericle Commercial Real Estate	Industrial and business park on reclaimed mine land	Enterprise & Socio-Economic Development; Ecological Restoration	Reclaims acid-generating mine waste for commercial infrastructure; >6,000 jobs created; a national model for mine-land redevelopment[90]
	Truetown Pigments (Ohio)	Ohio University; Rural Action; ODNR	AMD treatment for pigment production	Water Management; Enterprise Development; Employment Generation	Converts iron precipitates from AMD into marketable pigments; remediates streams; builds local circular-economy enterprise[91]
	Lynch Historic Mine Portal Revitalization (Kentucky)	Harlan County Fiscal Court; Portal 31 Heritage Project; Local Entrepreneurs	Cultural and eco-tourism revitalisation around historic mine infrastructure	Recreation & Tourism; Heritage Conservation; Community Enterprise	Addresses flooding in abandoned mine portals and restores a heritage coal-mine exhibit; includes

[89] Portal 31 Heritage Museum (2018)

[90] Mericle Commercial Real Estate (2021)
[91] Ohio Department of Natural Resources (2022)

					renovation of a company bathhouse and creation of small tourism enterprises; expected to create 20 permanent jobs and boost regional culture-based economy.[92]
	Dante Community Revitalization & Trail System (Virginia)	Dante Community Association; Virginia Dept. of Mines; Local Partners	Community revitalisation and trail development on abandoned mine corridors	Recreation & Tourism; Community Development; Employment Generation	Transforms old mine and rail routes into multi-use trails linking downtown Dante, St Paul, and local landmarks; enhances recreational tourism, creates 8 indirect jobs, and stimulates $1.17 million in local economic activity.[93]
	Quality Flooring Business Redevelopment (Illinois)	Quality Flooring Inc.; Coal Country Chamber of Commerce	Small-enterprise establishment on reclaimed mine land	Enterprise Development; Employment Generation;	Converts abandoned slag piles into commercial property for

[92] Harlan County Fiscal Court (2022)
[93] Dante Community Association (2023)

				Industrial Reuse	flooring manufacturing; demonstrates adaptive reuse of mine land for rural enterprise; awarded *Business of the Year (2007).*[94]
	Kayenta Industrial Park Infrastructure (Navajo Nation, Arizona)	Kayenta Township; Navajo Nation; U.S. Economic Development Administration	Industrial Park expansion and infrastructure development	Enterprise Development; Employment Generation; Economic Diversification	Extends utilities, sewer, and road networks on reclaimed mining areas to attract industries; offsets regional job loss from coal closures; enables sustainable growth in Navajo Nation.[95]
	Pittsburgh Airport Innovation Campus (Pennsylvania)	Allegheny County Airport Authority; PA DEP; Private Investors	Business and logistics park on reclaimed mine land	Enterprise Development; Employment Generation; Infrastructure Reuse	54 acres of mine-scarred land reclaimed for innovation campus; employs >1,200 construction workers and creates 7,000 direct & indirect jobs; leverages

[94] Illinois Dept. of Commerce (2007)
[95] U.S. Economic Development Administration (2023).

					$250 million in private investment[96]
	Ideal Fabricating & Aladdin Steel Expansion (Illinois)	Ideal Fabricating Inc.; Aladdin Steel LLC; Illinois Dept. of Commerce	Industrial reuse of reclaimed mine area for manufacturing facilities	Industrial Redevelopment; Employment Generation; Enterprise Development	Two major manufacturing firms operate on rehabilitated mine lands, creating 80 jobs; illustrating mine-to-manufacturing transition in small towns.[97]
	Maryland AMD Remediation & River Restoration Program	Maryland Dept. of Environment; Local Watershed Groups; EPA	Mine-drainage remediation and ecological restoration of pre-SMCRA coal sites	Water Management; Ecological Restoration; Employment Generation	Eight alkaline-dosing systems have been installed since 1992 to treat acid mine drainage; improved regional water quality; created 40 full-time equivalent jobs and $3 million economic impact.[98]
	East Kentucky Advanced	Kentucky Dept. of Education;	Vocational training and certification	Training & Skilling; Employment	Provides certifications in computer-

[96] Allegheny County Airport Authority (2022)
[97] Illinois Dept. of Commerce (2007)
[98] Maryland Dept. of Environment (2020)

	Manufacturing Institute	East KY AMI Foundation	for post-coal workforce	Generation; Community Development	numerically controlled manufacturing; trained 300 students by 2024; develops technical skills aligned with regional industrial growth.[99]
	Hopi Wellness & Veterans Memorial Center Expansion (Arizona)	Hopi Tribe; U.S. Department of Interior; Community Health Programs	Community-centre redevelopment & public-health infrastructure	Community Development; Health & Wellness; Education Infrastructure	Reconstructions and expands 1977 facility with new meeting spaces & demonstration kitchen; enhances health programs and social cohesion for Hopi communities[100]

[99] Kentucky Dept. of Education (2024)
[100] Hopi Tribe (2023)

Annex B: Mine Reclamation & Remediation

In the Indian context, technical reclamation, which refers to the engineering and physical restoration of mined-out areas, is the first stage of post-mining restoration - the primary goal is to create a stable, erosion-resistant landform which may be used for future ecological restoration or productive use (CCO, 2025). The main activities include:

- Topsoil Management: Strip and preserve topsoil before mining. Stored in regulated stockpiles (≤3m height, stable slopes) with drainage and turfing. Reapply within 2–3 years, enriched with compost or organic matter.
- Overburden Handling: The Ministry of Coal and the Ministry of Environment, Forest and Climate Change (MoEFCC) advise minimising the creation of external dumps. Overburden produced during mining should be directly backfilled into de-coaled voids via internal dumping. If external dumps are unavoidable, they must be engineered, stabilised, and later rehandled.
- Backfilling & Grading: Begin backfilling as voids become available during mining, carrying out sequential backfilling of de-coaled voids so landforms are progressively restored rather than waiting until mine closure. Implement progressive backfilling with layered compaction, shape final landforms to stable slopes with positive drainage, and reduce risks of erosion, landslides, and waterlogging.
- Final Landform and Topsoil Application: After backfilling and grading, re-spread preserved topsoil to support vegetation. Shape the final landform to blend with surrounding terrain and provide adequate drainage (contour drains, toe drains, sedimentation ponds). Where residual voids become water bodies, size them proportionally to pre-mining conditions and secure them with fencing, stabilised slopes, and controlled access.
- Drainage & Erosion Control: Install garland drains, contour bunds, check dams, and turfing. Use vegetation, coir mats, mulching, and grass seeding for erosion control.
- Hydro Reclamation: Abandoned pits may be converted into lakes, reservoirs, or fish farming areas. Assess void hydrogeology, hydrology, water quality and slope stability, manage water quality through sediment control, bioremediation and treatment of acid mine drainage. Apply engineering measures (benching, terracing, grading, bioengineering), safety controls

(fencing, access zones, signage), promote ecological succession and biodiversity. Conduct regular monitoring of water chemistry and biological indicators with adaptive management.
- Biological Reclamation: MoEFCC requires at least 33% of the leasehold area to be biologically reclaimed through a planned, phased plantation program. Use native grasses, legumes, hardy shrubs and fast-growing multipurpose trees (with community participation). Use nitrogen-fixing species, microbial inoculants and organic amendments to rebuild soil fertility. Employ mulching, contour trenches, rainwater harvesting and drip irrigation for moisture and erosion control. Apply water-based techniques (hydroseeding, hydromulching, wetland creation) and water-driven slope stabilization to assist succession and biodiversity recovery.

Soil Quality and Nutrient Criteria

Soil quality is defined as a core indicator in almost all studies assessing land for reclamation and regeneration. Herdiansyah et al. (2018) note that mining activities which intentionally remove vegetation change the composition of the soil which can cause erosion, sedimentation, loss in soil nutrients and soil compaction. Li (2023) identifies 11 criteria grouped under three major categories: land quality, soil nutrients, and engineering suitability. These criteria include effective soil depth, bulk density, alkali-hydrolyzable nitrogen content, phosphorus content, potassium, organic matter content, and soil texture. Threshold values are also specified; For example, organic matter above 30 g/kg and soil depth exceeding 30 cm are associated with higher suitability for agriculture (Li, 2023). These findings align with those of Bi et al. (2010), who applied a weighted index method to combine soil-related and surface-related characteristics for land reclamation at the Antaibao Opencast Mine in China. In this framework, soil fertility, erosion potential, and surface material (for example, bare rock, gravel, topsoil, etc) were essential in determining the land classes from Grade I (highest quality) to Grade IV (lowest quality) (Bi et al, 2010).

Remote sensing provides a method for assessing surface characteristics such as vegetation type and condition or soil properties such as texture, the presence of minerals, or moisture content (O'Donell et al. 2024). The USGS's Mined Lands Decision Support Tool identifies a very wide set of criteria to assess soil characteristics, including (but not limited to) soil type, pH, organic material, salinity, permeability. Using remote sensing and GIS data, Cao et al. (2025) similarly recommended soil pH and soil organic matter content as criteria to assess the suitability for cultivated land, grassland, and forest land. Fang et al. (2020) applied complex network theory to model how different soil parameters interact in reconstructed landforms. Their work reveals the importance of topsoil distribution and soil structural connectivity for post-mining land stability, which is needed even before vegetation is introduced. Waitkus (2022) further reinforces the importance of soil quality in his field study-based paper on repurposing surface mines in Wyoming, USA. The study outlines how compaction, infiltration rates, and topsoil thickness (all factors essential to establish a healthy soil type) should be routinely monitored to ensure sites are viable for grazing or native plant seeding.

Surface Topography and Stability

Kuhn (1998) notes that while reclamation requirements often necessitate restoring the landscape to its original contours (i.e., restoring original land forms), overburden and interburden materials substantially altered by excavation and weathering are not as likely to maintain stable slopes if put back to original contours which may make flatter slopes necessary. Holcombe & Bainton (2020) describe engineered backfilling and grading as prerequisites for any construction-heavy reuse project. Thus, slope and landform stability are also widely applied exclusion criteria, and are essential considerations for any PMLUs. In Cao et al. (2025), Li (2023), and Bi et al (2010), slope angle is considered a necessary parameter for most PMLUs, with slopes under 15° considered manageable for agriculture or other surface infrastructure. This aligns with terrain suitability considerations for solar installations and pumped-hydro energy storage explored in Krzemień et al. (2023), where land gradient affects layout feasibility and drainage. However, like soil quality, slope is treated inconsistently across studies. It is sometimes treated as a binary exclusion factor and sometimes as a part of a weighted scoring model. Another detailed example comes from the World Bank's LURA tool, which identifies three primary geotechnical hazards associated with slope instability in open pit mines: slope instability of the final mine slopes (or the slopes of spoils or other earth made structures), residual ground settlement of the lands above spoils or backfilled openings, and erosion of slopes or spoils either by water or wind. LURA uses a five-scale rating system across three criteria pertaining to geotechnical risks: Slope stability of mine or spoil slopes, residual ground settlement, and impact of groundwater rebound.

Surface structure, which includes subsidence, uneven settlement, and drainage feasibility, has been identified as another key set of criteria in multiple PMLU studies.

Li (2023) defines surface structure as "engineering suitability" of land and includes it in a final land suitability index via the Catastrophe Progression Method, a non-linear multi-criteria evaluation tool for classifying reclaimed coal mine land into four levels of suitability for agricultural reuse or environmental restoration. He et al. (2025) also discusses surface drainage and compaction in the context of loess soils, noting that reclaimed land must demonstrate acceptable hydrological flow and structural integrity to be viable for agricultural reuse. Similarly, the World Bank's LURA also identifies three criteria pertaining to the topography and hydrology of the mine site and important considerations for erodibility, water logging and hydrological flooding risks: surface gradient and relief, surface drainage, and frequency of extreme precipitation events.

Fang et al. (2020) show how spatial discontinuities in surface elevation and slope can undermine reclamation efforts, using network analysis to map areas at risk of hydrological disruption or mass waste. This suggests that even reclaimed land may require finer-scale terrain screening before repurposing. Finally, Waitkus (2022) outlines the use of landform shaping guidelines in Wyoming. As per state regulations, coal mines must be backfilled to approximate pre-mining topography. Additionally, companies and/or the local governing body should undertake compaction testing before sites are released for grazing or native vegetation establishment (Waitkus, 2022).

The criteria discussed above are often grouped together in literature; however, some studies also take an important step and distinguish between those criteria used for reclamation and those used for regeneration. As per the reviewed literature, reclamation criteria tend to prioritise engineering suitability (e.g., slope, drainage, and compaction). On the other hand, regeneration criteria focus more on environmental factors like nutrient content, soil structure, and vegetation potential. Thus, the suitability of a site for repurposing depends not only on its physical recovery (reclamation) but also on its biological readiness (regeneration). This has led to a call for a shift in thinking in mine land rehabilitation, one that integrates highly prescriptive 'environmental engineering' approaches with more descriptive systems-orientated 'ecological engineering' in order to harness natural forces in designing and recreating new ecosystems (Huang et al., 2022).

Water Quality and Soil Contamination

Much of the PMLU literature highlights the extreme importance of considering contamination of water (e.g., water quality) as screening criteria before repurposing sites for aquatic uses. The World Bank's LURA (2023) identifies acid mine drainage and soil contamination from heavy elements (especially in fly ash) and air pollution with dust and toxic microparticles as environmental risks associated with open pit mining. LURA uses a five-scale rating system across three primary criteria: presence of soil/groundwater contaminations or hazardous materials, environmental impacts of ongoing lignite production (dust, noise, vibrations, traffic, odors), and proximity to operating thermal power plants (TPPs), including after potential repurposing, lignite bunkers, fly ash stockpiles. For assessing and improving water quality (e.g., of bodies near the mine or located within the mine) LURA uses criteria like pH level (ideal range between 6.5-8.5), sulphate concentration (SO_4^{2-} < 1500 mg/L), and low sodium and heavy metals content. Miller et al. (2013), who studied selenium accumulation in pit lakes in Alberta, Canada, also showed that water contamination can render reclaimed sites ecologically unsuitable for fish habitats. Their findings support the idea that the presence of certain trace elements should be part of pre-repurposing assessments.

Although contamination is widely cited as a constraint, thresholds are rarely standardised. Many reports, including those by PwC in the Indo-German Energy Forum (2024) and ICMM (2019), highlight contamination as a challenge to repurposing but do not quantify safe levels or provide methods for field assessment. In the Indian context, Singh et al. (2024) recommend meeting the Central Pollution Control Board (CPCB) norms for class B water used as a threshold for aquaculture (pH 6.5–8.5, low heavy metals). However, Gwenzi (2020) argues that in post-mining and post-industrial ecosystems, conventional contamination thresholds may not adequately reflect risk, especially due to the massive, localised terrain differences that exist around the world. This highlights the need to integrate site-specific ecological information into standard contamination assessments.

The global transition away from coal-based energy has prompted countries to explore innovative ways of reclaiming and repurposing former mining sites. Once symbols of industrial growth, these landscapes are now being transformed into thriving spaces for renewable energy, ecological restoration, recreation, tourism, and community enterprise.

Across Europe, Asia, North America, and other regions, mine repurposing efforts demonstrate how post-mining landscapes can be turned into assets that support sustainable regional economies, promote biodiversity, and preserve industrial heritage. The following case studies illustrate twelve major international examples of coal mine repurposing, reflecting varied approaches and multi-sectoral collaborations across different contexts.

Campus Location
Plot No. 2, Rajiv Gandhi Education City, National Capital Region P.O. Rai, Sonepat Haryana-131029

Delhi Office
Ashoka University Office, 222, Second floor, Okhla Industrial Estate, Phase III, New Delhi-110020