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Towards a sustainable legacy: integrating net-zero targets into mine rehabilitation and closure planning

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Abstract

In alignment with the goals of achieving net-zero emissions and fostering a circular economy, this study explores innovative approaches for the relinquishment of lands following mine closure. It emphasises the integration of renewable energy sources, the cultivation of biofuels and the implementation of innovative natural battery storage technologies. By analysing a series of global case studies that highlight inventive practices for post-mining land use, this research outlines critical selection criteria and strategic planning recommendations to assist mine closure planners and mine operators in creating sustainable post-mining environments. To ensure a practical and informed approach, the study utilises a risk-based methodology to develop the selection criteria. Following this, a comprehensive strengths, weaknesses, opportunities and threats (SWOT) analysis is undertaken to systematically evaluate the strengths, weaknesses, opportunities and threats associated with each of these technologies for post-mining closure applications. This study maps a path for making mine closures a positive transition with sustainable assets and contributes to the broader journey towards environmental sustainability and circularity.

Keywords: *mine closure, legacy management, net-zero targets, renewable energy, asset transition, circularity*

1 Introduction

Net-zero emissions refer to achieving a balance between the greenhouse gases emitted into the atmosphere and those removed from it. This balance can be attained by reducing emissions through renewable energy, energy efficiency and carbon sequestration. Net-zero emissions is a crucial goal in combating climate change as it aims to limit global warming to 1.5°C above pre-industrial levels, as stipulated in the Paris Agreement (Yamashita & Fujii 2022). The importance of achieving net-zero emissions lies in its potential to mitigate the adverse impacts of climate change, including extreme weather events, sea level rise and biodiversity loss. Achieving net-zero emission targets is an essential component of global sustainable development; supporting ongoing economic growth that does not compromise environmental health and social wellbeing.

The mining industry is a significant contributor to global greenhouse gas emissions, accounting for approximately 4–7% of global CO_2 equivalent (CO_2e) emissions, according to the International Energy Agency (IEA 2021). CO_2e refers to the number of metric tonnes of CO_2 emissions with the same global warming potential as one metric tonne of another greenhouse gas, calculated using Equation A-1 in 40 CFR Part 98 (United States Environmental Protection Agency (EPA)) (IEA 2021). These emissions primarily arise from the extraction, processing and transportation of minerals and metals, which are energy-intensive processes typically reliant on fossil fuels (IEA 2021).

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Traditional mine closure implementation can lead to adverse environmental impacts such as soil and water contamination, landscape degradation and biodiversity loss; this is often exacerbated by the loss of local employment and supporting business opportunities as well as a loss of regional economic contribution. Conversely, sustainable mine closure involves several key practices aimed at ensuring the long-term viability and environmental health of former mining sites (Laurence 2006). This is achieved by developing focused actions that result in rehabilitating the mined land to a native ecological state or preparing it for alternative uses that support ecological and socio-economic functionality (Siyongwana & Shabalala 2019). These alternative uses, when implemented, have historically focused on agriculture, forestry or recreational areas. However, as global greenhouse gas emission-, energy- and nature-based targets develop, repurposing of mine sites for renewable energy projects which help offset processing-related emissions and provide alternative sources of clean energy is gaining momentum. This includes assessment of opportunities for cultivating biofuel crops to improve soil health, and innovative pumped hydro storage as a natural battery storage solution. Furthermore, there is a shift from the traditional linear mono-sectoral approach of a take-make-dispose design towards a circular economic approach that requires restorative and regenerative design that focuses on utilising resources more efficiently, reducing mineral losses to mining 'wastes' and mitigating environmental impacts associated with these footprints (Gleeson 2023; Ghandashtani et al. 2022).

By investigating innovative approaches for land relinquishment post-closure, this research aims to identify successful practices and develop selection criteria for sustainable mine closure strategies. Evaluating the strengths, weaknesses, opportunities and threats (SWOT) analysis associated with low-emission post-closure practices, this study aims to create a practical framework for mine rehabilitation that aligns with net-zero goals, transforming mine closures into positive transitions that support environmental and economic sustainability.

2 Background

The mining industry is increasingly focused on reducing its carbon footprint through various net-zero emissions initiatives. Current decarbonisation models highlight multiple options for reducing emissions, including operational efficiency improvements, sustainable fuels and green electricity. Emphasis is placed on the significant emissions from haulage trucks and the potential for biofuels, hydrogen fuel cells and battery electric vehicles to mitigate these emissions (Legge et al. 2021). Renewable energy integration is another critical focus, with mining companies adopting solar, wind and geothermal energy to power operations (Anyadike 2023).

These initiatives are further supported by guidance on reducing Scope 3 emissions, and emphasising transparency and stakeholder collaboration (International Council on Mining and Metals [ICMM] 2023). Case studies demonstrate practical implementations of these initiatives. For example, Figure 1 illustrates various renewable energy systems which are operational, under construction or planned to be constructed in Australia (Strazzabosco et al. 2022; Igogo et al. 2021).

Figure 1 Planned, under construction and operational renewable energy systems in Australian mines

Several innovative approaches aimed at enhancing sustainability and achieving net-zero emissions targets across mine sites are summarised in Table 1.

Table 1 Description of innovative approaches in mine closure activities to achieve net-zero emissions

Innovative approaches	Description
Renewable energy integration	Mines are increasingly being repurposed for renewable energy projects. Solar farms, for instance, are being installed on rehabilitated land to provide clean energy and offset the carbon footprint of mining operations. This contributes to the local energy grid and promotes sustainable energy use (Chou et al. 2023)
Biofuel cultivation	Mines are exploring the cultivation of biofuels on rehabilitated lands by planting crops such as algae or switchgrass. These crops can be processed into biofuels, restoring the land and producing sustainable energy sources, and contributing to the circular economy (Harris et al. 2015)

Innovative approaches	Description
Natural battery storage	Innovative storage solutions like pumped hydro storage are being implemented in former mined pits. These systems store excess renewable energy by pumping water to a higher elevation during periods of low demand and releasing it to generate electricity during peak demand, making effective use of existing mine infrastructure (Australian Renewable Energy Agency [ARENA] 2023)
Re-using mine tailings and water resources	The re-use of mine tailings and water resources is gaining attraction. Tailings can be repurposed in construction materials or for land reclamation, and water from mining operations is being treated and reused, reducing the need for freshwater and minimising environmental impact (Amari et al. 2024)
Ecosystem restoration and biodiversity enhancement	There is a growing emphasis on restoring natural habitats and enhancing biodiversity through creating wetlands, forests or wildlife corridors on rehabilitated mined lands. These efforts aim to restore ecosystem functions, support local wildlife and provide recreational spaces for communities (Otto 2009)

The above examples indicated that practices in mine rehabilitation and closure are evolving towards more sustainable and innovative approaches. Enhanced ecosystem restoration and community engagement further ensure that mine closures provide lasting benefits for both the environment and local communities.

3 Methodology

The research design for this study is a mixed-methods approach that combines qualitative and quantitative analyses to explore the integration of net-zero targets into mine rehabilitation and closure planning. The study comparatively assessed various case studies to develop a list of selection criteria for identification of possible post-mining closure technologies; these were then evaluated using a SWOT analysis to provide a holistic evaluation of sustainable post-mining land use practices.

To assess global practices, case studies are selected from different continents, representing a variety of climatic, geological and socio-economic conditions. Case studies are chosen based on their implementation of innovative technologies and practices in renewable energy integration, biofuel cultivation and natural battery storage. The selection included mines operating under diverse regulatory environments to examine how different policies impact sustainable closure practices. Preference was given to projects with well-documented outcomes and data availability to facilitate analysis.

The following section provides an overview of the selected case studies. To develop a selection criterion for post-mining closure technologies, a risk-based methodology was employed. This methodology was initiated with risk identification, where environmental, technical, financial and social risks associated with each technology were determined.

The SWOT analysis for each post-mining closure technology systematically evaluated its strengths, weaknesses, opportunities and threats. The process reviewed the data from case studies, industry reports and academic literature. Strengths such as the high efficiency and scalability of solar energy systems were identified, while weaknesses such as the initial high costs and maintenance requirements of advanced battery storage systems were analysed. Opportunities for further development and integration, such as potential policy incentives for renewable energy projects in mining regions, were explored. Threats, including regulatory changes, market volatility and technological advancements that may impact the viability of the selected technologies, were also assessed.

3.1 Case studies

Four case studies that formed the basis for this study are introduced in the following section.

3.1.1 Case A

In Case A, an abandoned gold mine in Australia is being transformed into a renewable energy hub through a pumped storage hydro project. This project combines a 250 MW pumped hydroelectric storage facility with a 270 MW solar farm, utilising renewable energy to pump water between the pits and generate power during high-demand periods. This innovative approach reduces reliance on fossil fuels, supports the state's renewable energy targets and creates local employment opportunities.

3.1.2 Case B

In Case B, a mine in South Africa has integrated a 40 MW solar plant to power its operations. This renewable energy solution reduces the mine's dependence on the coal-powered national grid, cutting carbon emissions substantially. The solar plant will continue or expand to operate post-closure to support rehabilitation efforts, ensuring sustainable energy for environmental monitoring and site maintenance.

3.1.3 Case C

Case C, located in Australia, has developed a comprehensive mine rehabilitation and closure plan that heavily relies on renewable energy. The site is using solar power to treat and manage water quality during mine operations and will do so afterwards. This underpins the restoration of surface water bodies and groundwater to their natural state, supporting biodiversity and ecosystem health, and minimising the environmental impact of the mine closure process.

3.1.4 Case D

Case D involves a mine in Brazil that has adopted the cultivation of biofuels as an innovative approach to mine closure and rehabilitation. The mine site is being repurposed to grow biofuel crops, which not only aid in soil stabilisation and erosion control but also provide a sustainable energy source. The biofuel production supports local energy needs and offers economic opportunities for the surrounding communities. This approach helps restore the ecological balance of the area and contributes to carbon emission reduction by replacing fossil fuels with biofuels.

4 Selection criteria

The development of criteria for selecting low-emission post-mining closure technologies involves several key considerations to ensure sustainable and effective rehabilitation. These criteria must address environmental, social and economic factors, as well as potential risks and benefits. Based on this, the selected technologies should be:

- regulatory compliant
- environmentally sustainable
- economically viable
- socially acceptable
- technologically feasible.

Table 2 summarises how these criteria were applied in the identified case studies. By applying these criteria, the study shows that selected post-mining closure technologies not only support net-zero targets but also align with broader sustainability goals.

Table 2 Application of selection criteria to identified case studies

Criterion	Case A	Case B	Case C	Case D
Regulatory compliance	Met all environmental regulations and supported renewable energy targets	Met regulatory requirements for renewable energy use	Ensured compliance with water quality and environmental restoration regulations	Complied with agricultural and environmental regulations for biofuel production
Environmental sustainability	Solar power to pump water, minimising ecological disruption and supporting biodiversity	Solar powerplant reduced dependence on coal power, promoting sustainable energy use	Solar-powered water treatment restored water bodies, supporting biodiversity	Biofuel crop cultivation stabilised soil, controlled erosion and supported biodiversity
Economic viability	Provided local jobs and reduced fossil fuel dependence, lowering operational costs	Long-term energy cost savings	Cost-effective water treatment using solar power, reducing long-term operational costs	Generated revenue from biofuel production, supported local energy needs, provided economic opportunities for communities
Social acceptance	Created jobs and supported local economy, enhancing social sustainability	Provided sustainable power for ongoing monitoring, gaining community support	Enhanced water quality, benefiting local ecosystems and gaining community approval	Created local jobs, supported community development, gained community acceptance through biofuel projects
Technological feasibility	Proven solar and hydroelectric technology used effectively in the project	Solar power technology applied successfully to meet energy needs	Solar power technology effectively used for continuous water treatment	Proven biofuel cultivation techniques suitable for local environmental conditions

5 Strengths, weaknesses, opportunities and threats analysis

The SWOT analysis provided an evaluation of the strengths, weaknesses, opportunities and threats associated with renewable energy, biofuels and natural battery storage technologies in post-mining closure applications. This analysis helped identify the potential benefits and challenges of implementing these technologies in rehabilitated mine sites. Table 3 details the outcomes of the SWOT analysis of the case studies identified, summarised as follows:

- Renewable energy technologies (e.g. solar and wind power), supported by pumped hydroelectric storage systems, are the most suitable and immediate solutions for repurposing mine sites. They offer significant environmental and economic benefits, aligning with global sustainability goals.
- Biofuels, while promising, require further advancements and strategic integration with agricultural practices to become a more practical option.

Table 3 Strengths, weaknesses, opportunities and threats analysis results on technologies used in case studies

Technology	Strengths	Weaknesses	Opportunities	Threats
Solar power	**Environmental benefits:** Significant reduction in carbon emissions, minimal ecological disruption **Economic savings:** Long-term energy cost savings and reduction in operational costs by replacing fossil fuels **Regulatory compliance:** Strong support for renewable energy targets and adherence to environmental regulations	**High initial costs:** Significant upfront investment required for infrastructure set-up **Maintenance requirements:** Need for regular maintenance to ensure system efficiency and longevity **Land stability:** Closed mines may have unstable land due to subsidence or erosion, which could affect the installation and long-term stability of solar panels **Energy storage and grid integration:** Storing and integrating the solar energy into the grid can be challenging, especially if the closed mine is in a remote location with limited grid access **Climate:** The local climate may not be conducive to solar energy production year-round, affecting the efficiency and output of the solar panels	**Technological advancements**: Continued innovation can enhance efficiency and reduce costs **Regulatory incentives:** Increasing support and incentives from governments for sustainable energy practices **Community engagement:** Potential to create jobs and engage local communities in renewable energy projects **Early integration:** Installing solar power during project development can reduce operational costs and offset some of the closure capex	**Economic fluctuations**: Variability in economic conditions may impact funding and financial viability **Regulatory changes:** Changes in regulations could impose additional costs or operational constraints

Technology	Strengths	Weaknesses	Opportunities	Threats
Pumped hydroelectric storage	**Utilisation of existing infrastructure:** Closed mined pits can be repurposed with minimal structural changes for pumped hydro storage, making use of the existing topography **Large-scale storage capacity**: Pumped hydro storage systems can handle large amounts of energy, making them suitable for grid-scale storage and balancing **High efficiency:** This method of energy storage is one of the most efficient, with the ability to quickly respond to energy demand fluctuations **Long lifespan:** Pumped hydro systems have a long operational life, providing a long-term energy storage solution **Proven technology:** Pumped hydro is a well-established technology with a track record of reliability and effectiveness	**Environmental impact:** The construction and operation of pumped hydro storage may have ecological impacts, such as affecting water quality and local habitats **High initial investment:** The upfront costs for developing pumped hydro storage facilities can be significant **Water requirement:** Pumped hydro storage requires a substantial amount of water, which may not be readily available in all mine locations **Regulatory challenges:** Obtaining the necessary permits and approvals for water usage and modification of closed mine sites can be complex and time-consuming **Energy storage and grid integration:** Storing and integrating the energy into the grid can be challenging, especially if the closed mine is in a remote location with limited grid access	**Renewable energy integration**: Pumped hydro storage can be integrated with other renewable energy sources to create a more stable and reliable energy supply **Energy transition:** As the world moves towards renewable energy, pumped hydro storage can play a crucial role in energy transition strategies **Innovation:** There is potential for technological advancements to improve the efficiency and reduce the environmental impact of pumped hydro storage **Economic revitalisation**: Repurposing closed mines for energy storage can bring new economic opportunities to former mining regions	**Competition from other technologies:** Other energy storage technologies, such as batteries, may offer more flexibility or lower costs in certain applications **Climate change:** Changes in precipitation patterns could affect the availability of water for pumped hydro storage systems **Public perception:** There may be public resistance to altering former mine sites, especially if there are concerns about environmental impacts **Policy and market risks**: Shifts in energy policy or market dynamics could affect the long-term viability of pumped hydro storage projects

Technology	Strengths	Weaknesses	Opportunities	Threats
Biofuel cultivation	**Environmental benefits:** Stabilises soil, controls erosion, supports local energy needs, and provides sustainable energy **Economic opportunities:** Generates revenue from biofuel production and supports local economies **Land availability:** Closed mines can provide large tracts of land that are already cleared and may not be in use, thus avoiding the land-use conflicts associated with biofuel crop cultivation in other areas **Reduced competition with agriculture:** Since closed mines are typically not suitable for traditional agriculture, using them for biofuels does not compete with food production	**High initial costs:** Significant upfront investment required for establishing biofuel crops **Market volatility:** Prices of biofuels can be subject to significant fluctuations **Soil quality:** Mines often leave behind poor soil conditions and contamination **Climate suitability:** The success of biofuel cultivation depends heavily on local climate conditions, which may not always be favourable, leading to potential crop failure or reduced yields **Water availability:** High water requirements for biofuel crops can strain local water resources, particularly in regions already facing water scarcity	**Technological advancements:** Innovations in biofuel production can improve efficiency **Regulatory incentives:** Government support for sustainable agricultural practices and renewable energy	**Economic fluctuations**: Variability in economic conditions may impact funding and financial viability **Community opposition**: Potential for opposition if not adequately engaged and informed about benefits

By prioritising these technologies, mining sites can effectively transition to sustainable post-closure land uses, contributing to broader net-zero targets and environmental sustainability. However, these technologies require further investigation and strategic planning to recommend the practical pathways for application in mine closure (MacNamara 2024).

6 Strategic planning

In this section, three strategic plans — an integrated approach for incorporating the discussed technologies in mine closure planning, recommended policy implications and the importance of stakeholder engagement — are elaborated.

6.1 Integrated approach

An integrated approach to mine closure planning should incorporate renewable energy, biofuels and natural battery storage to achieve sustainability and net-zero targets. This holistic strategy ensures that post-mining landscapes are not only rehabilitated but also contribute positively to the environment and local communities.

6.1.1 Renewable energy integration

Implementing solar farms and wind turbines on rehabilitated lands can be a crucial step towards generating clean energy and reducing reliance on fossil fuels. These technologies not only provide sustainable power to nearby communities and industries but also contribute to the broader goal of reducing greenhouse gas emissions. By utilising vast expanses of post-mining landscapes, solar and wind power installations can harness natural resources to produce significant amounts of energy. For instance, solar farms with large arrays of photovoltaic panels can convert sunlight into electricity, while wind turbines capture kinetic energy. This dual approach maximises energy generation and ensures a continuous supply of clean energy, promoting energy security and environmental sustainability (Strazzabosco et al. 2022). Hybrid energy systems that integrate solar, wind and battery storage technologies can significantly improve the dependability and performance of renewable energy initiatives by ensuring a stable and reliable power supply. This integration is critical for the success of intermittent technologies like solar and wind as it addresses the variability in energy production and enhances grid stability by storing excess energy during peak generation periods and releasing it when production is low or demand is high. By employing these combined systems, rehabilitated lands have the potential to be transformed into robust energy hubs of renewable energy production. These systems integrate multiple renewable sources to optimise energy production and storage, ensuring a stable power supply even during periods of low solar irradiance or wind activity. Battery storage systems play a critical role in these hybrid set-ups by storing excess energy generated during peak production times and releasing it when demand is high, or production is low. This approach not only maximises the utilisation of renewable energy resources but also enhances grid stability and reliability, making renewable energy a more viable and consistent option for powering communities and industries. Moreover, integrating renewable energy systems such as solar and wind power during the initial project development and operational phases can significantly reduce operational costs and offset closure capital expenditure, thereby enhancing the overall economic viability of energy projects on rehabilitated lands.

6.1.2 Biofuel cultivation

Growing biofuel crops on mined lands offers a sustainable and productive use of these areas. These crops can be cultivated specifically for biofuel production, contributing to renewable energy supplies while simultaneously improving soil health through carbon sequestration. Switchgrass, for instance, is a hardy perennial that can thrive on marginal lands, providing biomass for biofuel without competing with food crops. Algae, on the other hand, can be grown in ponds or bioreactors, efficiently converting sunlight and CO_2 into biofuels. The cultivation of these biofuel crops on rehabilitated mine lands can turn otherwise unproductive areas into valuable resources for renewable energy production. Utilising organic waste from mining operations and local agriculture to produce biofuels promotes a circular economy and reduces waste. This approach not only addresses waste management challenges but also provides a sustainable source of biofuels. By converting organic waste into biofuels, mining sites can reduce their environmental impact and support local economies. This process involves collecting organic waste materials, such as plant residues and agricultural byproducts, and processing them into biofuels through methods like anaerobic digestion or fermentation. The resulting biofuels can be used to power various applications, from transportation to electricity generation, thus reducing dependency on fossil fuels and contributing to a more sustainable energy system (Harris et al. 2015).

6.1.3 Natural battery storage

Converting former mine pits into pumped hydro storage facilities (Figure 2) provides an innovative solution for storing excess renewable energy and stabilising the energy grid. Pumped hydro storage involves using excess energy to pump water from a lower reservoir to an upper reservoir during periods of low energy demand. When demand is high, the stored water is released back down to generate electricity through turbines. This method is highly efficient and offers a large-scale energy storage solution that can provide reliable power during peak demand periods. By repurposing former mine pits, this approach not only utilises existing infrastructure but also transforms these areas into valuable assets for renewable energy storage. Implementing large-scale battery storage systems, such as lithium-ion and advanced flow batteries, complements renewable energy projects by providing efficient energy storage and supporting grid stability (Igogo et al. 2021). These battery systems can store energy generated from renewable sources during periods of excess production and release it when needed, ensuring a continuous and reliable power supply. Lithium-ion batteries are widely used due to their high energy density and efficiency, while advanced flow batteries offer longer discharge times and scalability. By integrating these battery storage technologies with renewable energy projects, the overall efficiency and reliability of the energy system are significantly enhanced, making renewable energy a more practical and dependable option for meeting energy demands.

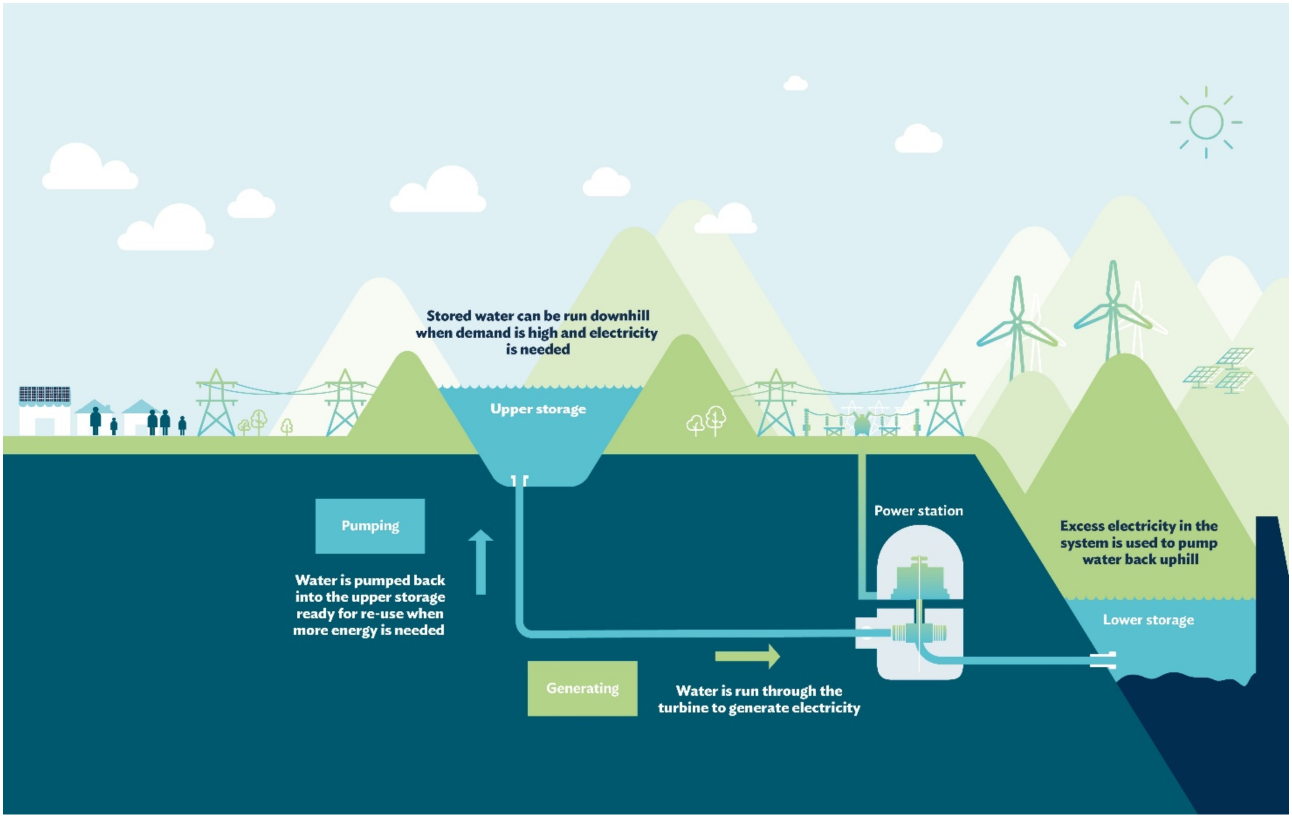

Figure 2 How pumped hydro energy storage works (Hydro Tasmania 2018)

By adopting an integrated approach that incorporates renewable energy, biofuels and natural battery storage, mine closure planners can transform post-mining landscapes into sustainable, productive and environmentally friendly areas.

6.2 Policy implications

To support sustainable mine closure practices, several policy changes and initiatives are recommended in the following sections.

6.2.1 *Incentives for renewable energy projects*

Providing tax credits, grants and subsidies for renewable energy projects on rehabilitated mine lands can significantly reduce the initial investment burden and encourage the adoption of clean energy technologies. Financial incentives are essential in making renewable energy projects more attractive to investors and developers. By offering tax credits, governments can reduce the overall tax liability for companies that invest in renewable energy infrastructure, making it a more financially viable option. Grants and subsidies can provide direct financial support to offset the high upfront costs associated with renewable energy installations, such as solar panels and wind turbines. These incentives promote the adoption of clean energy technologies and also stimulate economic growth by creating jobs and supporting local industries involved in renewable energy projects. Implementing feed-in tariffs ensures that renewable energy producers receive a guaranteed price for the electricity they generate, further enhancing the financial viability of renewable projects. Feed-in tariffs provide a stable and predictable revenue stream for renewable energy producers, encouraging more investments in renewable energy infrastructure. This policy mechanism ensures that renewable energy projects are financially sustainable by guaranteeing a fixed price for the energy they produce, regardless of market fluctuations. By providing a secure and attractive financial environment, feed-in tariffs can drive the expansion of renewable energy capacity on rehabilitated mine lands, contributing to the overall transition towards a more sustainable and resilient energy system.

6.2.2 *Regulatory support for biofuels*

Developing and enforcing standards and certifications for sustainable biofuel production is crucial to ensuring that biofuels contribute to environmental goals without compromising food security or biodiversity. Standards and certifications provide a framework for sustainable biofuel production, setting guidelines for practices that minimise environmental impact and promote the use of non-food biomass. These regulations ensure that biofuel production does not compete with food crops for land and resources, protecting food security and preserving biodiversity. By adhering to these standards, biofuel producers can demonstrate their commitment to sustainability, gaining consumer trust and support from regulatory bodies. Allocating funding for research and development (R&D) in advanced biofuels and sustainable cultivation practices is essential for promoting innovation and efficiency in the biofuel sector. Investment in R&D can lead to the development of new biofuel technologies that are more efficient, cost-effective and environmentally friendly. Funding can support research into second-generation biofuels, which use non-food biomass and waste materials, reducing the impact on food supply and land use. Additionally, sustainable cultivation practices can enhance the productivity and environmental benefits of biofuel crops. By prioritising R&D, governments and industry can drive advancements in biofuel technology, making it a more viable and sustainable alternative to fossil fuels.

6.2.3 *Facilitating energy storage solutions*

Developing policies that facilitate the integration of energy storage systems into the national grid is critical for enhancing grid reliability and supporting the widespread adoption of renewable energy. Streamlined permitting processes and interconnection standards can reduce the regulatory barriers for energy storage projects, making it easier and faster to deploy these technologies. By simplifying the approval process and establishing clear guidelines for interconnection, governments can encourage the development of energy storage infrastructure. This integration is essential for managing the variability of renewable energy sources such as solar and wind, ensuring a stable and reliable power supply. Encouraging innovation in energy storage technologies through funding and regulatory support is vital for continuous improvement and cost reduction in storage solutions. Investment in R&D can lead to breakthroughs in energy storage technologies, improving their efficiency, capacity and lifespan. Regulatory support can provide a conducive environment for testing and deploying new storage solutions, facilitating their entry into the market. By supporting innovation, governments can help reduce the costs associated with energy storage, making it more accessible and practical for widespread use. Improved energy storage solutions are key to maximising the benefits of renewable energy, providing a reliable backup power source and enhancing grid stability.

Implementing supportive policies and regulatory frameworks is essential for the successful integration of renewable energy, biofuels and energy storage solutions in mine closure practices. These measures will reduce financial barriers, promote sustainable practices and facilitate the development of advanced technologies, ensuring that post-mining landscapes contribute to environmental sustainability and economic growth.

6.3 Stakeholder engagement

Engaging stakeholders is crucial for the success of sustainable mine closure projects. This includes local communities, governments and industry partners, each playing a vital role in the planning and implementation process.

6.3.1 Local communities

Involving local communities in the planning and decision-making process is crucial to the success of sustainable mine closure projects. Inclusive planning ensures that the needs and concerns of the local population are addressed, fostering trust and cooperation. When communities are actively involved, they are more likely to support and engage with the projects, leading to more successful and widely accepted outcomes. This approach not only improves the relationship between mining companies and local residents but also empowers the community by giving them a voice in the future use of the 'land'. Such engagement can include regular consultations, public meetings and participatory decision-making processes, ensuring transparency and mutual understanding. Developing projects that provide tangible benefits to local communities further enhances their support and engagement (Siyongwana et al. 2019). These benefits can include job creation, improved infrastructure and access to renewable energy. By demonstrating the positive impacts of mine closure projects, such as new employment opportunities in renewable energy installations or infrastructure development, communities are more likely to view these initiatives favourably. Ensuring that projects deliver real and lasting benefits helps build a positive legacy and can transform former mine sites into valuable community assets. This approach not only aids in the socio-economic development of the region but also promotes long-term sustainability and resilience.

6.3.2 Government and regulatory bodies

Working closely with government and regulatory bodies is essential for developing policies that support sustainable mine closure practices. Policy collaboration involves creating a regulatory framework that encourages innovation and sustainability in post-mining land use. This can include developing standards for environmental protection, incentives for renewable energy projects and guidelines for sustainable land rehabilitation. Collaborative efforts between mining companies and regulatory agencies can ensure that policies are both practical and effective, promoting sustainable development while protecting environmental and community interests. Ensuring continuous monitoring and compliance with environmental and safety regulations is critical for maintaining transparency and accountability throughout the project life cycle. Regulatory bodies play a vital role in overseeing mine closure activities to ensure that they meet established standards and do not harm the environment or public health. Regular inspections, environmental assessments and compliance audits help maintain high standards and build public trust. Transparency in reporting and accountability measures can demonstrate a commitment to responsible mine closure and sustainable practices, reinforcing the credibility and legitimacy of the projects.

6.3.3 Industry partners

Fostering public-private partnerships between the mining industry, renewable energy companies and other stakeholders is key to pooling resources and expertise. These partnerships can drive large-scale projects and ensure their financial and technical viability. By collaborating, industry partners can leverage their collective strengths, share risks and achieve more ambitious goals than they could independently. Public-private partnerships can facilitate the deployment of advanced technologies, attract investment and enhance the overall impact of mine closure projects. This collaborative approach ensures that projects are well-supported, financially robust and technically sound. Encouraging knowledge sharing and collaboration among industry partners is essential for disseminating best practices and innovative solutions in mine rehabilitation and closure. Platforms for exchanging information, such as industry conferences, workshops and collaborative research initiatives, can foster a culture of continuous improvement. By learning from each other's experiences and innovations, industry partners can adopt more effective strategies and technologies, enhancing the overall success and sustainability of mine closure projects. Knowledge sharing helps build a repository of successful practices and lessons learned, contributing to the advancement of the industry as a whole.

Effective stakeholder engagement is essential for the success of sustainable mine closure projects. By involving local communities, collaborating with government and regulatory bodies, and fostering partnerships within the industry, mine closure planners can ensure that these projects are inclusive, well-supported and sustainable, ultimately leading to positive environmental and social outcomes (Banfield et.al 2023).

7 Conclusion

This study highlights the role that innovative approaches play in contributing towards achieving sustainable post-mining land uses aligned with net-zero emissions and fostering circular economy principles. The analysis of global case studies offers a pathway for implementing these technologies, emphasising the importance of strategic planning and stakeholder engagement. This approach not only mitigates the environmental impacts of mining but also contributes to broader sustainability goals, ensuring that post-mining landscapes provide long-term ecological and economic benefits.

The research shows that the successful implementation of these technologies requires a risk-based methodology to develop selection criteria, alongside a SWOT analysis to evaluate their strengths, weaknesses, opportunities and threats in terms of environmental sustainability, economic viability, social acceptability, technological feasibility and regulatory compliance. The case studies illustrate how these criteria can be applied in practice, providing valuable insights into the practical challenges and benefits of integrating solar power energy, biofuels and natural battery storage into mine closure planning.

One of the critical takeaways from the study is the need for an integrated approach that combines multiple technologies to maximise the sustainability and efficiency of post-mining land uses. Renewable energy projects such as solar and wind farms can generate clean energy and reduce greenhouse gas emissions, while biofuel cultivation can restore soil health and produce sustainable energy. Natural battery storage solutions like pumped hydro storage can provide reliable energy storage and support grid stability. Furthermore, the study emphasises the importance of policy support and stakeholder engagement in achieving successful mine closures. Financial incentives, regulatory frameworks and continuous monitoring are essential to promote the adoption of sustainable practices. Involving local communities, governments and industry partners in the planning and implementation process ensures that projects are inclusive, well-supported and aligned with local needs and priorities. This collaborative approach enhances the social and economic benefits of mine closures, transforming them into positive transitions that contribute to the overall goal of net-zero emissions.

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