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Water and energy integration towards post-mine transition

C Clerc *The University of Queensland, Australia*

V Sharma *The University of Queensland, Australia*

L Pagliero *The University of Queensland, Australia*

Abstract

Mining is resource-intensive and often located in remote and climate-fragile areas with limited resources, requiring complementary developments in water treatment and power generation services to sustain its activities (Owen & Kemp, 2018). Communities that surround mine sites usually rely on the mining company for their water and energy supply. Since many jurisdictions require mining companies to close all service infrastructure as part of closure planning, mine closure raises concerns over the future sustainability of this mining-dependent infrastructure. Mine closure, therefore, can disrupt critical access to water and energy for local communities and impact their post-mining transition plans and development opportunities (Christmann, 2017; Vivoda et al., 2019).

Interest in exploring the socio-economic impacts of mine closure has been increasing worldwide. Yet, research that considers how mine closure intersects with local needs to align sustainable planning is sparse (Bainton & Holcombe, 2018). Understanding the nature of water and energy challenges induced by mine closure in remote and climate-vulnerable regions will help guide communities to successfully transition post-mining (Carvalho, 2017). As such, an integrated approach to water and energy access and security is needed.

Integrated planning of water and energy access allows the optimal use of resources, enabling a sustainable supply post-mining. Silo-ed interventions that promise a clean and affordable supply of energy without considering its interface with, and role in, sustainable water management, have been ineffective in achieving sustained benefits over the long term (United Nations et al., 2014). An integrated approach not only helps balance resource quality and quantity for productive livelihoods but, in doing so, optimises the cost-efficiency of solutions while minimising associated social and environmental impacts (De Oliveira et al., 2022).

This paper presents an exploratory study of what an integrated multi-dimensional analysis for water and energy access post-mine may look like. The novelty of our approach is its grounding in inter-disciplinary literature encompassing diverse disciplines: mining and mine closure, development challenges in remote contexts, climate change adaptation, and integrated energy and water regional-scale planning.

Keywords: *socioeconomic transition, planning, integration, water, energy*

1 Introduction

Water and energy are essential resources to sustain human activities with dynamic interactions along their supply chains. Water systems require energy to pump, distribute, and treat water, as well as energy systems use water for cooling, extraction, and production (Van Dijk, 2015). At the same time, the supply of water and energy impacts the ecosystem by using resources and releasing waste, therefore, intensive use in any area will have lasting implications. Understanding these socio-ecological interactions is critical to balancing water and energy use, maintaining their quality and quantity to sustain community livelihoods, productive activities, and ecosystem functionalities (Lee et al., 2021).

Reliable and affordable water and energy access are doubly exposed to the impacts of climate change and the intensity of consumption resulting from economic growth. Climate change disrupts water and energy sources and infrastructure, impacting their security of supply. Within economic activities, the mining industry stands out for its intensive water and energy use, leading to the degradation and depletion of local sources (Carvalho, 2017). As mine sites are usually located in remote and climate-fragile areas with limited resources, the impacts of mining entail complex socio-environmental implications for local livelihoods and economic activities that extend beyond the closure of the mine (International Council on Mining and Metals, 2021).

Mine closure adds further challenges to the reliable water and energy supply, as local communities often rely on the mining infrastructure to compensate for their limited access to these services (UNDP Bangkok Regional Hub & UN Environment, 2018). The main barriers to successfully addressing these challenges are linked to the lack of clear standards and regulations to manage the social and economic impacts of closure (Owen & Kemp, 2018). Closure strategies for water and energy supply aligned with local needs can support communities' post-closure transition. Integrated planning of water and energy access incorporating the trade-offs between systems will allow the optimal use of resources for their sustainable supply post-mining (Carvalho, 2017).

Studies have analysed alternative solutions for water and energy supply after mine closure. Research has been mainly focused on using mining infrastructure for water storage and energy generation, without incorporating interactions between the systems or the requirements for their successful operation after closure (Frejowski et al., 2021; Winde, 2020; Winde & Stoch, 2010). Apart from infrastructure, post-mine solutions require ensuring local management and maintenance capabilities to sustain their long-term operation (Toledano & Roorda, 2014). Moreover, identifying water and energy challenges for effective closure planning requires a deep understanding of the local context, including the stakeholders involved, existing infrastructure, projected demand, management capabilities, and the role of various administrative systems (De Oliveira et al., 2022; Owen & Kemp, 2018).

This paper uses a multidisciplinary approach to better understand the synergies between water and energy dynamics and challenges in mine closure contexts, in order to inform integrated strategies to address these challenges. The main focus of our analysis is the alignment of integrated water and energy solutions with post-mining development planning. Through this review, the paper aims to influence better practice in mine closure planning, with specific reference to local stakeholder needs and regulatory environments.

2 Research methods

A narrative literature review was conducted using the Scopus database for literature searching. A combination of keywords was applied for title searching according to the aim and topic of the research, using the following terms: energy, water, integration, mining, mine closure, climate, sustainability, sustainable development, and planning. Peer-reviewed journal articles, conference proceedings, books, and book chapters were included in the search. The search was extended to industry and institution reports. Only publications after the year 2000 were selected to ensure the use of updated information. After reviewing the alignment of the literature identified with the aim of this research and avoiding repetition, 47 documents were selected for analysis. Additionally, 3 web sources with supporting information have been included in this review.

Although the narrative review provides a focused selection of literature on the topic, it allows an improved understanding around water and energy challenges post-mine together with opportunities and limitations for integration. Key elements and knowledge gaps identified are analysed in the following sections.

3 Review of literature

Strategies towards socio-economic development are supported by essential water and energy services (United Nations et al., 2014). In the past, water and energy provision have been managed separately, usually through ineffective solutions as increased efficiency in one sector pushes demand in the other sector (Hussey & Pittock, 2012). Integrated water and energy supply can take advantage of their synergies to promote improvements in both sectors, allowing sustainable provision and use of water and energy over the long-term (United Nations et al., 2014; Van Dijk, 2015). This integrated approach is especially beneficial in post-mining contexts since ongoing water and energy supply are among the greatest socio-economic challenges of closure (Carvalho, 2017).

3.1 Water and energy integration, a sustainable path

The nature of water and energy dynamics is highly complex. Understanding these dynamics, including the socio-ecological trade-offs around water and energy use, can encourage the design of sustainable strategies to support socio-economic growth while protecting the ecosystem (Lee et al., 2021). Water and energy strategies that incorporate the impacts of one system into another enable the design of optimal systems to provide reliable and equitable access in the long-term (De Oliveira et al., 2022).

Integrated water-energy systems include infrastructure, devices, technologies, as well as management and governance schemes. This integrated approach allows minimising the social and environmental impacts from isolated supply systems, such as overexploitation of resources and uneven distribution of services, while optimising the cost-efficiency of solutions. In a mine closure context, an integrated approach to planning water and energy supply can promote a balanced use of natural, economic, and institutional resources to support sustainable local development (De Oliveira et al., 2022).

3.1.1 Water and energy challenges towards sustainable development

To promote common sustainability objectives and facilitate decision-making, the United Nations proposed 17 Sustainable Development Goals (SDGs) by 2030, including essential water and energy services. SDG 6 is focused on the human rights to access clean water and sanitation systems, with billions of people still lacking safe drinking water. SDG 7 states the need to access affordable, reliable, and clean energy sources, with one-third of the global population still using unsustainable cooking systems, and under a billion lacking access to electricity. Today, water scarcity, security of supply, and the increasing demand for energy with rising prices, are the main global challenges to achieving water and energy SDGs (United Nations, 2021).

Water and energy challenges are interrelated in line with their natural dynamics, driven mostly by the social structures that frame their consumption towards economic growth, as shown in Figure 1 (Lee et al., 2021). Strategies to sustain increasing water and energy needs have mostly focused on economic principles rather than ensuring their long-term quality and availability, impacting on the security of water and energy supply (Chapin et al., 2009). The cumulative impacts of intensive water and energy use have led to climatic and economic pressures given the overexploitation of resources and increasing prices to access, which in turn increase the vulnerability of water and energy sources, creating a vicious cycle (Van Dijk, 2015; Vinca et al., 2021).

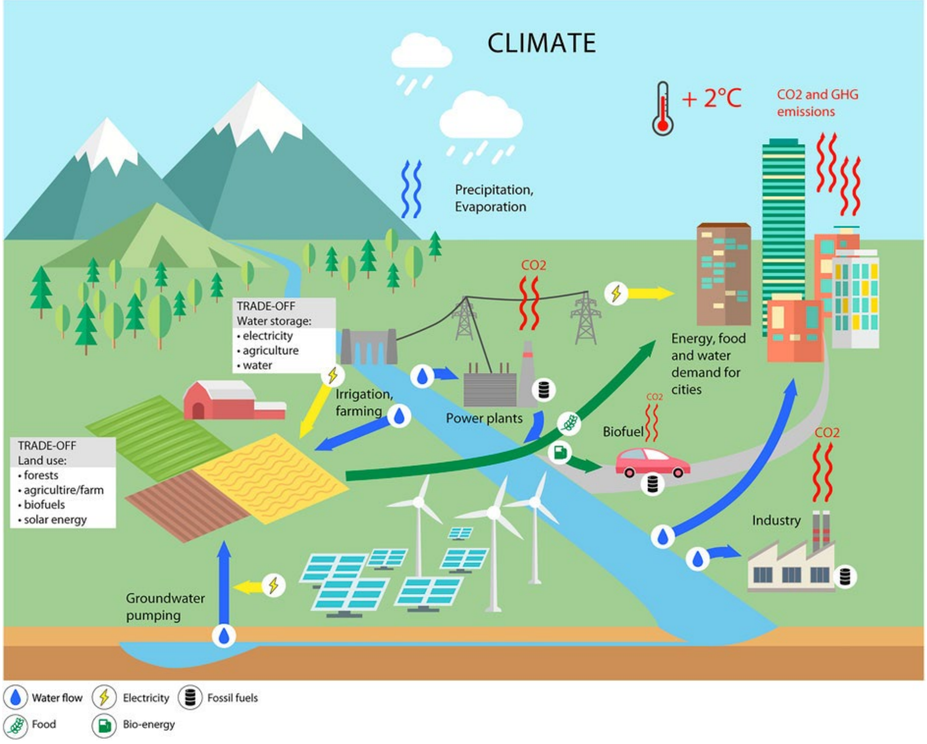

Figure 1 Water, energy, and climate interactions (Vinca et al., 2021)

The variable nature of climate dynamics has exposed the interactions between water and energy sustainability challenges, hindering the design of strategies to address them. Droughts reduce water availability, heat waves increase water and energy needs, as well as cyclones can affect the quality of water reservoirs and the security of water and energy supply infrastructure. At last, the consequences of climatic changes on water and energy systems have had severe impacts on communities' livelihoods (IPCC, 2012).

Strategies to balance water and energy consumption could help address some climatic and economic impacts. Yet, solutions have been mostly isolated, aiming for emissions reduction within energy generation and ensuring water supply for food security, which have been insufficient to address their interrelated challenges towards sustainable development (Hussey & Pittock, 2012). Some isolated solutions, such as energy-intensive desalination plants, have paradoxically increased the demand for water and energy, intensifying the conflicts around access, security of supply, and climatic pressures (Scott et al., 2011). In consequence, isolated solutions without incorporating water and energy synergies have led to unaffordable and inaccessible supply for vulnerable people, limiting their development alternatives (Hussey & Pittock, 2012).

3.1.2 Integrated water-energy systems

Considering the increasing global demand for water and energy and the interrelated challenges, an integrated approach seems favourable to sustain local livelihoods and ecosystem functionalities. Integrated water and energy systems can improve access to reliable, affordable, and equitable supply, reducing dependency on external sources and promoting sustainable use of local resources (De Oliveira et al., 2022; Nina et al., 2014). A few approaches have proposed the analysis of water and energy synergies to guide integrated systems, however, the employment of market criteria to efficiently allocate resources and the lack of social and ecological considerations, have led to increased competition, prices, and barriers to access (Williams et al., 2019).

Despite the limitations, the Water-Energy Nexus (WEN) approach has supported the analysis of optimal designs for integrated water-energy solutions. Thus, desalination plants and recycling systems powered by renewable energy have been identified as the most efficient alternatives for reliable and affordable water supply in remote

Greek islands and the Sahara region (Papapostolou et al., 2020; Ramirez et al., 2021). In Alaska, the high electricity costs, dependence on imported diesel, and communities' preferences, have led to hybrid renewable microgrids as the most optimal alternative to power water systems (Chamberlin et al., 2021). The local context has been critical in the selection of technological solutions.

Modelling tools have also been designed to guide integrated water-energy systems. The Spatial and Temporal Nexus Water-Energy model (SPATNEX-WE) identifies the most cost-efficient balance between water and energy production and consumption, which has empirically demonstrated that integrated solutions can be more cost-effective and resource-efficient than isolated alternatives (Khan et al., 2018). The Stockholm Environment Institute integrated WEAP and LEAP software, widely used for water and energy planning, seeking a decision tool that incorporates synergies between systems. The tool enabled the analysis of optimal water and energy supply alternatives in California aligned with climatic projections, but without considering social factors such as the requirements for the effective management of solutions (Mehta & Yates, 2012).

These initiatives have revealed the importance of incorporating social considerations in the design of water and energy solutions, and the engagement of stakeholders to support their effective implementation. For instance, in remote locations with limited water and energy supply infrastructure, locally managed solutions tend to be more cost-effective than centralised alternatives. As local management skills often need to be developed, engaging stakeholders in the design of solutions is key for their effective operation (Aberilla et al., 2020). In addition, incorporating a comprehensive analysis of the institutional requirements to implement integrated water-energy systems in the design stage will ensure their successful implementation (Williams et al., 2019).

3.1.3 Integrated planning of water and energy supply

Governments are responsible for ensuring reliable water and energy provision and raising awareness about the importance of their sustainable use (United Nations et al., 2014). Among government instruments, carbon credits and water charges have been able to reflect the scarcity of resources while ensuring their affordable access (Bone et al., 2011). But the isolated management of water and energy provision has not been successful in promoting their sustainable use, requiring a more comprehensive approach (Carvalho et al., 2019). UNESCO has promoted integrated water-energy planning to encourage their reliable supply and sustainable use in order to support economic growth and social wellbeing (United Nations World Water Assessment Programme, 2014).

Integrated water and energy planning entail complex limitations given their independent management structures. Water is often managed locally, while energy tends to have a broader scope (Carvalho et al., 2019). These asymmetries led to several challenges, including matching priorities on supply and demand, balancing the cost-efficiency of solutions, incorporating climatic impacts on resource availability, and working under fragmented regulations with unclear responsibilities. Better collaboration between water and energy institutions could support flexible instruments towards integrated planning (De Oliveira et al., 2022; Oliver & Hussey, 2015).

Policies and regulations are required for the adequate implementation of integrated water-energy strategies. Understanding the impacts of water policies on energy demand and vice versa, will allow identifying mechanisms to integrate their synergies within regulatory instruments guiding private and public sectors toward sustainable planning (United Nations et al., 2014). Hence, incorporating energy efficiency methods in water regulations, and water protection mechanisms in energy policies, will support coordinated planning (Hussey & Pittock, 2012). Socio-ecological dynamics should also be integrated. Subsidise schemes considering the depletion of resources could better address the risks, as well as price reforms incorporating resource distribution and consumption arrangements could promote equitable access (Ramirez et al., 2021). Efficiency programs and monitoring systems have revealed socio-ecological dynamics within water and energy use (Hussey & Pittock, 2012).

Coordination between governments, industries, and communities will allow identifying common objectives and management schemes to sustain the strategies, while raising awareness about the importance of sustainable use of resources. A successful example of participatory planning is Zaragoza's Smart Water and Energy strategy, which has included citizens and public entities in decision-making around water and energy efficiency. Likewise, Indonesia's energy and water development strategy has supported initiatives for safe water supply and local energy generation, empowering communities to manage the solutions (United Nations et al., 2014).

A summary of key considerations for the effective design, implementation, and planning of integrated water-energy systems is presented in Table 1.

Table 1 Considerations for integrated water-energy systems

Consideration	Challenges	Strategies
Comprehensive Design	Multidimensional Analysis of Trade-offs is critical to ensure the Sustainability of Integrated Systems	Deep Understanding of Local Context, including Social, Techno-Economic, Environmental, and Institutional Aspects
Incorporation of Social Aspects	Limited Alignment with Local Needs, Preferences, and Capabilities	Stakeholders' Engagement in the Decision Process
Cross-sectoral Coordination	Unbalanced Priorities, Multi-scale Management, Fragmented Regulations, and unclear Responsibilities	Identify common institutional Goals towards flexible Regulations to sustain an Integrated Planning
Governance and Management	Lack of Capabilities to locally manage Integrated Systems	Transfer of Knowledge and Skills for Local Management and participatory Governance

3.2 Water and energy dynamics in mine closure

Mining is a critical activity for human development since most products, infrastructure, and technologies require minerals and metals for production (Carvalho, 2017). However, mining is highly disturbing to local livelihoods and ecosystems (Unger et al., 2020). Although mining tends to improve local conditions for economic growth, the often unequal distribution of benefits and the limited strategies to uphold them after closure have hindered the sustainability of mining practices in the long-term (Hobbs, 2005). The increasing global demand for minerals and metals in line with demographic changes, technological innovation, and the shift to green energy, has intensified the pressure on resources that sustain extractive activities, such as land, energy, and water (Christmann, 2017).

Closure of mine operations entails additional impacts on local resources and communities. Strategies to address these impacts have been largely focused on their environmental consequences. While the socio-economic aspects of closure have been vaguely explored, lately, concern has increased especially around implications on water and energy access in remote and resource-dependent regions and their repercussions on local development (Monosky & Keeling, 2021). Understanding water and energy dynamics in mine closure contexts is, therefore, critical to promote alignment of closure practices with local needs towards a successful socio-economic transition post-mine.

3.2.1 Socio-economic impacts of closure

Closure has remained one of the biggest challenges of the mining sector, with diverse impacts and limited guidelines. The social impacts of closure encompass cultural, institutional, and socio-economic consequences, including disruptions in local economic structures and the requirements for a successful transition post-closure (Unger et al., 2020). These impacts, in most cases, are driven by social dynamics during mine operations, such as demographic changes, governance schemes, and the availability of infrastructure and services, including water and energy. Consequently, the effective management of the social impacts of closure needs to be considered early within the planning of the mining project (Bainton & Holcombe, 2018).

A good example of closure of mine operations without considering their socio-economic implications, is the mono-industrial area of Jiu Valley in Romania. The sudden closure of mines reduced employment opportunities leading to out-migration. However, as miners' skills are valuable in the energy sector, a study identified that supporting renewable energy projects in post-mine regions may offer pathways to mitigate the social impacts of closure while promoting diversified economic alternatives (Izabella et al., 2021). Including socio-economic aspects within the design of closure strategies can enable a successful post-mine transition.

The socio-economic impacts of mine closure extend beyond employment opportunities. Disruption of socio-ecological systems by closure practices also has severe consequences for local livelihoods and economic activities. Particularly, closure of critical water and energy supply infrastructure can limit the local development opportunities to transition post-mine (Owen & Kemp, 2018). Strategies to ensure ongoing water and energy supply in line with local needs can, therefore, support socio-economic wellbeing after closure (UNDP Bangkok Regional Hub & UN Environment, 2018).

3.2.2 Water and energy supply post-closure

Mining activities are water and energy intensive, with several challenges associated along the mine life cycle. Initiatives to address water and energy mining challenges have focused on balancing the cost-efficiency of supply solutions, improving management strategies, and promoting efficiency technologies. However, the socio-economic impacts of mining on water and energy systems remain unaddressed (UNDP Bangkok Regional Hub & UN Environment, 2018). About closure, water and energy supply initiatives have been limited, mostly seeking land and infrastructure reuse for water storage, geothermal, and hydropower systems. Yet, the management and maintenance arrangements of these solutions have not been adequately analysed to ensure their effective operation post-mine (Frejowski et al., 2021; Winde, 2020; Winde & Stoch, 2010).

Mining companies can contribute to providing access to reliable infrastructure for water and energy supply and transferring skills for their effective management post-closure (Izabella et al., 2021; Monosky & Keeling, 2021). These practices can benefit companies by developing trust and reputation, as the example of the Australian Gulf Communities Agreement (Everingham & Keenan, 2017). Although some governments have taken advantage of these benefits to include water and energy supply infrastructure within mine permits, responsibilities around their provision and management post-closure remain unclear. The lack of clear standards and regulations to address post-mine water and energy challenges generates concerns in local communities about the economic landscape after closure, particularly in cases with longstanding mine operations (Owen & Kemp, 2018).

In cases where the mine oversaw the provision and maintenance of water and energy infrastructure, poorly planned closure without coordination has led to ineffective solutions (Toledano & Roorda, 2014). For example, Minas Conga in Peru built water storage infrastructure to improve supply for communities in order to mitigate the removal of four lakes for mining activities. But the lack of stakeholder engagement and increased perception of water damage led to the suspension of mining operations (Downs et al., 2020). Likewise, the sudden closure of the Mhangura mine in Zimbabwe caused a significant water shortfall for communities, given their inability to pay for the maintenance of mining-related supply infrastructure (Toledano & Roorda, 2014).

Stakeholders' participation in decision-making has supported sustainable water and energy supply post-mining. The Bulyanhulu mine in Tanzania built water supply infrastructure designed by the local government and transferred management skills to communities for their successful operation after closure (Toledano & Roorda, 2014). Rio Tinto in the Pilbara region of Australia built infrastructure to use coastal waters instead of their water rights, allowing protection of local water sources in line with government plans (Gomez, 2011). Woodlawn Mine in Australia built a bioreactor for the local community, which uses the electricity generated and recovers compost and heat from the process to sustain agricultural activities (Australian Government, 2016).

Infrastructure for shared use by mining and communities is another alternative for water and energy supply post-mine. Oversizing water and energy infrastructure, considering the needs of mining operations and surrounding communities, will allow optimising the cost of the systems while promoting mining integration in the local economy. However, the lack of trust between communities and mining companies and the unclear regulatory frameworks have hindered the implementation of shared infrastructure (Toledano & Maennling, 2018). In some cases, partnerships between governments, companies, and communities to co-design water and energy infrastructure have promoted the incorporation of shared solutions into closure plans (United Nations et al., 2014). Thus, Ashanti's Geita mine in Tanzania partnered with the local council to build water infrastructure for shared use and transfer skills for local operation post-closure (Toledano & Roorda, 2014).

A recent example of skills transfer is the Municipal Capability & Partnership Programme in South Africa, a collaborative initiative between mining companies, local governments, and research institutions. The program aims to improve local governance capabilities in mining towns to mitigate risks associated with the delivery of essential services post-closure. The initiatives developed within the program have focused on better management of water towards reliable access and local maintenance of infrastructure (Municipal Capability & Partnership Programme, 2022). These initiatives introduce opportunities for a successful transition post-mine.

In sum, initiatives focused on the provision of infrastructure post-closure require a participatory design and adequate management schemes with a fair distribution of responsibilities. Early and participatory closure planning is critical to ensure the sustainability of supply strategies post-mine (UNDP Bangkok Regional Hub & UN Environment, 2018). A summary of strategies to provide water and energy supply after closure, and the requirements for their effective operation, is presented in Table 2.

Table 2 Strategies for water and energy supply post-closure

Supply Strategies	Requirements for Operation
Optimise Mining Consumption and encourage Alternative supply during Operations to allow the Availability of Resources Post-Mine	Align with Local Needs and Development Opportunities Post-closure
Re-purpose of Mining Supply Infrastructure Post-closure	Consider Local Resources and Capabilities for effective Management and Operation
Design Shared Supply Infrastructure and transfer it Post-closure	Stakeholders' Engagement in the Design of Post-mine Solutions considering suitable Management and Governance Schemes

3.2.3 Mine closure planning

Closure planning allows incorporating sustainable practices into mining activities ensuring their long-term benefits (World Business Council for Sustainable Development & International Institute for Environment and Development, 2002). The International Council on Mining and Metals (ICMM) has been working to encourage cooperative planning in addressing environmental and social aspects of closure, and to support the socio-economic development of communities in which mining operates (International Council on Mining and Metals, 2021). In this line, the ICMM guide for Integrated Mine Closure (Figure 2) recommends progressively addressing environmental, social, and economic risks during the mine's operational life as a strategy to support sustainable closure, understanding closure planning as a cyclic process (International Council on Mining and Metals, 2019).

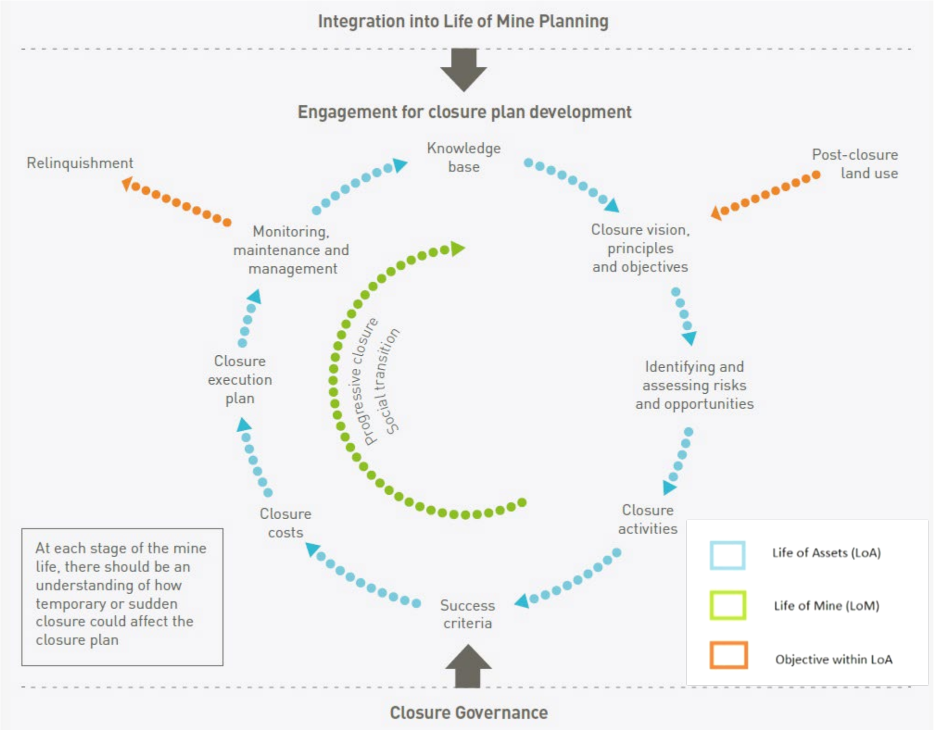

Figure 2 Integrated mine closure planning (International Council on Mining and Metals, 2019)

Within the integrated mine closure process proposed, water and energy systems should be considered at all stages throughout the life of assets, whether re-purposing mining assets or as closure activities, aiming to support the social transition at the end of the mine's life. To date, requirements for closure have not been standardised across the mining industry.

Mine closure practices have usually aligned with local regulations, mainly focused on removing infrastructure, managing waste, and land use alternatives, with limited attention to the social impacts of closure (Bainton & Holcombe, 2018). Closure planning has been an inconsistent process within the industry given the lack of clear regulations, limited stakeholder engagement, inadequate impact assessment, and ambiguous mitigation strategies (Monosky & Keeling, 2021). This is particularly concerning as several mine sites worldwide are expected to close over the next few decades (International Council on Mining and Metals, 2021).

The unclear standards for closure have led to additional impacts. In Australia, for instance, a common land rehabilitation practice for closure is selling assets to communities that can obtain value from mine waste, usually compromising rehabilitation efforts. Further, it is possible to declare the mine under care and maintenance and avoid fulfilling closure requirements, even for decades (Unger et al., 2020). Currently, several mine sites remain abandoned across Australia (Vivoda et al., 2019). Improving the institutional capacity and regulations to support the implementation of closure practices is critical for its sustainable planning (World Business Council for Sustainable Development & International Institute for Environment and Development, 2002).

The effective management of closure impacts allows reducing the cost of mitigation strategies while sustaining the company's reputation (Dzakpata et al., 2021). Effective closure planning also benefits communities and governments by creating opportunities for economic development, providing jobs and improving critical infrastructure such as electricity and sanitation (Winde & Stoch, 2010). Consequently, mine closure planning should include all stakeholders involved to incorporate all related impacts (Dzakpata et al., 2021; International Council on Mining and Metals, 2019). Communities' knowledge of local risks and needs is critical for comprehensive closure planning. Similarly, governmental plans can be aligned with post-mine transition strategies to ensure the sustainable management of resources (Edwards & Maritz, 2019).

Overall, early and participatory closure planning could lead to sustainable decisions aligned with stakeholders' aspirations and challenges, optimising resources while empowering communities in decision-making (World Business Council for Sustainable Development & International Institute for Environment and Development, 2002). For instance, in New Caledonia, the government and the community decided to invest dividends from mining in local economic diversification by supporting infrastructure and services, thus contributing to a better distribution of benefits toward sustainable economic growth post-mining (Kowasch, 2018). Nevertheless, stakeholders' engagement in closure plans is scarce, given the lack of clear standards to incorporate their demands into decision-making (Monosky & Keeling, 2021).

Some initiatives are underway to guide an informed and sustainable socio-economic transition post-mining. The Australian Cooperative Research Centre for Transformations in Mining Economies (CRC TiME) developed a framework for participatory closure that focuses on socio-environmental risks (Dzakpata et al., 2021). The University of the Witwatersrand in South Africa proposed a guideline to address the socio-economic aspects of closure along the mine life cycle, supporting diversified economic opportunities (Stacey et al., 2010). The World Bank Group published a toolbox to guide governance frameworks for mine closure (World Bank, 2021). Although there is no evidence of the application of these initiatives, they are expected to guide effective practices if supported by adequate regulations.

4 Conclusion

Water and energy are critical resources to sustain livelihoods and support economic growth. In mine closure contexts, ongoing water and energy supply are among the main socio-economic challenges. As water and energy dynamics are interrelated, a multi-dimensional analysis of challenges towards water and energy access post-closure will allow identifying optimal supply solutions aligned with local development plans post-mine. Integrated water-energy systems enable optimal, cost-effective, and efficient solutions while protecting the ecosystem, maintaining its capacity to sustain water and energy supply in the long-term. Effective integration requires a better understanding of the local context, including stakeholders' needs and capabilities, in order to design optimal solutions supported by coordinated management.

Research on water and energy integration has focused attention on optimising water and energy consumption to advance cost-effective systems. Similarly, initiatives for water and energy supply post-mine have mostly pursued isolated solutions for infrastructure reuse without addressing management requirements or local plans. Further research around integrated water-energy solutions with a special focus on mine closure planning will encourage the analysis of optimal alternatives and supporting regulations towards a sustainable socio-economic transition post-mine.

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