Engineering our way to safe and sustainable mining

EngineeringX

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Introduction

The Lloyd's Register Foundation (2024) World Risk poll identified mining as one of the most dangerous professions in the world.[1] This spotlight explores the projected expansion of mining in response to the growing global demand for minerals and the role of engineers, governments and industry in meeting the required safety and environmental requirements.

While the formal and regulated mining industry has worked hard over the last decade to improve worker safety and to mitigate the environmental impacts of mining, progress has been variable across regions and countries and more remains to be done.[2] Growing demand for materials due to increased electrification and the shift to renewable energy infrastructure, coupled with the nature of extraction operations, may increase the environmental, economic and social impact of extraction in the future.[3]

Another significant challenge is the growth in artisanal and small-scale mining operations. These unregulated operations can be extremely hazardous, as workers do not necessarily follow the established safety requirements and can increase adverse environmental impact.

There is no single definition of 'safe' or 'sustainable' mining. In this spotlight we refer to the adoption of practices which ensure the safety and fair economic benefit of local populations and workers, while also keeping environmental harm as low as reasonably possible and remediating damage caused.

The three stakeholder groups of the ECI 2024 — engineers, government and industry — all play a critical role in promoting and adopting safer and more sustainable mining practices. While a key component is government regulation, regulations alone are not sufficient. Professional engineers are needed to design and implement technologies that minimise and mitigate harm; and the mining industry must be able to retain these engineers so that its activities are managed by experienced professionals.

1 Lloyd's Register Foundation (2024) World Risk Poll. https://wrp.lrfoundation.org.uk/news/mining-and-quarrying-named-among-the-most-dangerous-occupations-in-the-world.

2 Joughin, N.C. (2011) Engineering considerations in the tolerability of risk. Journal of the Southern African Institute of Mining and Metallurgy, 111(8), 535. In this study Joughin argues that accident statistics in deep gold mines in south Africa are within tolerable levels of risk as defined by the Health and Safety Executive (HSE) in England in the UK in a 2011 study. The majority of fatalities have been related rather to illegal mining operations. See also annual number of fatalities per 100,000 workers in the Australian mining industry since 2004 from Cliff, D. How safe are Australia's mines? The Conversation, published online: March 18, 2024 and highlighted below under engineering industry.

3 Critical Materials: demand side resource efficiency measures for sustainability and resilience. Pg.21-22. See also https://nepc.raeng.org.uk/critical-materials.

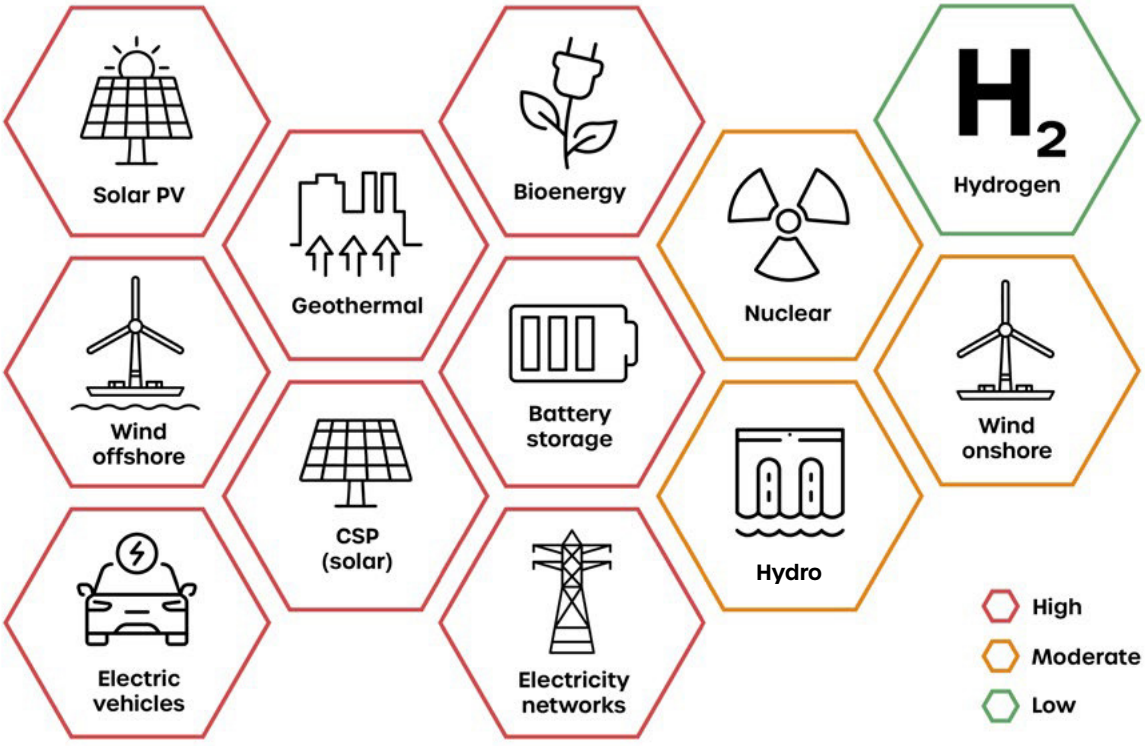
What engineering challenges need to be overcome for safer and more sustainable mining?

Growing demand

Growing demand on the mining industry is being driven in part by expanding use of battery and renewable energy technology,[4] which requires metals such as copper, lithium, and cobalt.

Copper is key to meeting the expanding demand for electrification and is used to modernise ageing power generation and transmission infrastructure to accommodate renewable sources. Achieving net-zero emissions by 2050 is already translating into a rapid growth in copper demand, which was forecast to increase by more than 82% between 2021 and 2035.[5]

Figure 1: Presence of copper in energy transition technologies



Note: CSP = concentrated solar power. Increased grid transmission and distribution investments are not considered in the copper intensity assessment of each technology as it

4 Hund, K, et. al. (2020) Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition. World Bank Group.

5 S&P Global Market Intelligence The Future of Copper.

Transportation is also electrifying quickly, with rapidly growing sales of electric vehicles further pushing unprecedented demand for copper as well as lithium, nickel and cobalt. On the supply side, copper production is currently highly concentrated in two countries, Chile and Peru. These two countries account for over a third (38%) of global production of the raw material, while China accounts for 40% of the refined copper produced globally.[6] A large proportion of the global supply of lithium is extracted from an area in the Andes known as the lithium triangle, home to many Indigenous communities and an important wildlife ecosystem.[7] Congo is responsible for over 70% of global cobalt. Increasing the global supply of copper and other minerals in the short term will therefore be essential to achieve a global energy transition, requiring an expansion of mining activities. However, to reduce the environmental and human impact of this transition, in the long-term this must be accompanied by implementing more 'demand-side' measures, aimed at reducing the need for critical materials including through better infrastructure planning, innovative design, and increasing materials recovery, reuse and recycling.[8] Effective collaboration of engineers, government and the mining industry is needed to ensure that mineral demand and supply is managed more safely and sustainably.

Environmental protection

In addition to fears over loss of land and livelihoods, the potential for environmental degradation often sparks conflicts between mining companies, local communities and the government. Engineers have a crucial role to play in minimising environmental harm through effective design and sustainable methods. To achieve this, engineers must work with their industry to prioritise mitigating environmental damage and biodiversity loss.

Government regulation of mining companies is also essential. Chile, the world's largest copper producer, is eager to balance the demands of economic development and environmental protection. In June 2023, Chile passed a bill establishing the Biodiversity and Protected Areas Service (BPAS), aiming to safeguard 21% of the country's territory and 43% of its Maritime Exclusive Economic Zone. While its National Lithium Strategy seeks to increase lithium production, the BPAS effectively bans concessions in national parks, natural monuments and virgin reserves, while permitting them in national reserves and conservation areas with comprehensive environmental management plans in place. This legislation aims to intensify environmental scrutiny for projects in protected areas, affecting the mining, energy, fishing, and forestry sectors. It also aims to empower local communities and activists to challenge projects in or near protected areas through legal means.

6 S&P Global Market Intelligence The Future of Copper.
7 Exhausted: how we can stop lithium mining from depleting water resources, draining wetlands and harming communities in South America, 2022. Natural Resources Defense council as quoted in NEPC and RAENG (2024) Critical Materials: demand side resource efficiency measures for sustainability and resilience. Pg 21. See also https://nepc.raeng.org.uk/critical-materials
8 NEPC and RAENG (2024) Critical Materials: demand side resource efficiency measures for sustainability and resilience. Pg.21-22. See also https://nepc.raeng.org.uk/critical-materials.

The growth in artisinal mining

As described above, strong safety and environmental concerns exist in relation to artisanal and small-scale mining (ASM). Although the exact number of artisanal miners is not known, the World Bank estimates that 45 million people globally are engaged in ASM directly, with potentially as many as 225 million both indirectly and directly engaged in the sector,[9] with the demand for minerals driving further growth. This includes demand for gold and precious stones as well as minerals used in a variety of technological applications. For example, ASM-mined tin and tantalum make up 25% of global supply.[10]

Artisanal mining is often characterised by manual techniques and minimal technology and is undertaken by people, including children,[11] working in hazardous conditions. The informal nature of many artisanal operations complicates regulation, and it is illegal in many countries. For this reason, artisanal miners often operate covertly in abandoned mines, lacking the necessary engineering skills and resources for safe working conditions. These operations may result in environmental damage, especially when conducted through open-pit, shallow mining methods. For example, artisanal and small-scale gold mining is a primary source of mercury releases in Latin America and the Caribbean, posing significant environmental risks.[12] To address this issue, many countries have signed the Minamata Convention of Mercury treaty,[13] aiming to protect human health from the toxic effects of mercury. In Colombia, the government passed Law 1658/2013 in 2013, which restricts the marketing and industrial use of mercury in mining. The law sets a goal to eliminate mercury use in all industrial and productive processes within ten years, and within five years for mining specifically. However, the implementation of this law has faced challenges due to the lack of detailed legal and technical procedures, the rise in mercury smuggling, and informality in the mining sector.[14]

What key roles do the industry, government and professional engineers play in achieving safer and more sustainable mining?

The three stakeholder groups outlined in the ECI 2024 — professional engineers, government and the engineering industry — play pivotal roles in reducing the damage to ecosystems and communities and addressing the challenges to achieving safer and more sustainable mining practices.

9 Achieving Sustainable and Inclusive Artisanal and Small-Scale Mining (ASM): A Renewed Framework for World Bank Engagement. September 2024, The World Bank
10 Ibid.
11 "This is what we die for": Human rights abuses in the Democratic Republic of the Congo power the global trade in cobalt, 2016. Amnesty International
12 Nature based solutions towards more responsible mining in Brazil | Global Mercury Partnership
13 Minimata Convention on Mercury
14 All that glitters is not gold or platinum: Institutions and the use of mercury in mining in Chocó, Colombia. Extractive Industries and Society, 5(3), 308–318. http://doi.org/10.1016/j.exis.2018.03.011

Professional engineers

Mining is a complex industry that demands a diverse range of skills and disciplines, with engineers playing a critical role at every stage of a mining project. From the initial exploration and discovery of minerals to the final restoration of the land, engineers are responsible for designing and implementing safe and efficient operations. While there are limits to what any individual engineer can change or achieve while operating within the wider global system, there remains much that individual creativity, engineering innovation and dedication to the values of sustainability, safety and equity can impact within any given mining operation.

For example, mining engineers oversee the planning and management of operations, ideally ensuring efficient mineral extraction while prioritising safety, environmental impact and economic factors. Geological engineers assess geological formations to determine the quality and quantity of deposits and overall feasibility of projects, while environmental engineers develop strategies for waste management, water treatment and land reclamation to promote sustainability.

Mechanical and electrical engineers design the machinery and systems used in mining, ensuring reliability and safety. As mining operations grow deeper and more technologically advanced, electronic and computer engineers are increasingly vital for enhancing safety and productivity through robotics and telecommunications. Civil engineers focus on constructing essential infrastructure, such as roads and tunnels, while process engineers work on optimising mineral extraction and processing.

Engineers and engineering can play a vital and positive role in reducing the risks of mining and in improving its sustainability. To manage this, in parallel with changes in government and industry-driven priorities, engineers need to understand environmental conservation and resource management. They need to be well-versed in renewable energy technologies and their integration into mining operations to reduce carbon emissions and promote a low-carbon future. This includes expertise in sustainable materials and waste management practices. It also includes the use of innovative techniques for recycling and reusing materials, as well as implementing circular economy principles to minimise waste generation. With many competing responsibilities, mining engineers must have the highest level of organisational skills.

Government

Governments must manage many of the tensions around mining. On the one hand, mining provides critical resources for economic development and can be a motor to help develop more advanced engineering capacities.[15] At the same time, governments play a critical role in setting and enforcing legislation and regulations to guide the mining industry towards safer and more sust ainable practices.

15 In the ECI 2024, mining data was used as one of the proxies for the regulatory framework fostering safe and sustainable engineering.

This can be approached, as in Chile, by defining where mining can and cannot take place, for example by excluding designated protected zones. Legislation can also dictate how mining takes place, for example through rules around community engagement and environmental protection. This is increasingly important as international consumers and companies demand more responsibly sourced products and incorporate a greater focus on supply chain sustainability.[16]

In Colombia, for example, the government has recently developed a new mining code.[17] This complex initiative aims to formalise the activities of artisanal miners, but its ultimate effectiveness is still uncertain.[18] The government is engaging in extensive consultations and held a mining summit in May 2023, incorporating the summit's conclusions into the new mining law. Proposed plans include establishing a state-owned mining company to purchase minerals from individual miners and defining rules for managing mining concessions.[19] This entity would also contribute to the exploration of mining products necessary for Colombia's energy transition. The new mining code also emphasises the protection of water rights for local populations.[20]
Communication between government, communities and mining companies is critical for reviewing and adapting environmental regulations to local conditions, considering factors such as diversity, inclusion, origin and culture. Communication with regulatory bodies is also important to establish clear rules and procedures that benefit all interested parties.

The involvement of all key stakeholders in the discussion about how to develop mineral resources is critical for determining, in each context, if and how mining operations can bring tangible benefits to the communities who live alongside these resources.

The Canadian government meanwhile is grappling with its role in ensuring effective collaboration with local and Indigenous peoples in areas where the mining industry is looking to expand operations. In October 2023, the Supreme Court of Canada ruled the Impact Assessment Act[21] largely unconstitutional, limiting the federal government's regulatory power. However, the Canadian government released its final United Nations Declaration on the Rights of Indigenous Peoples Action Plan, emphasising the need for consultation and involvement in projects. Despite these measures, conflicts persist, as seen in the Ring of Fire project, which has been accused of not fully involving all the First Nations tribes whose territory the project will impact.[22] Efforts to advance Indigenous interests are intensifying, with some First Nations communities filing court claims and disrupting public meetings.

Another area of government engineering capacity is in regulations and enforcement around mine closures. Mines that are not closed properly can attract illegal mining activity that can put people, communities and the environment at risk.[23] The Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development (IGF) conducted a survey in 2019 and early 2020 to evaluate how

16 https://www.newscientist.com/article/2434514-inside-the-sustainable-supply-chain-revolution/ (retrieved 8 June 2026)
17 Elements of Colombia's new Mining Law revealed - MINING.COM
18 https://news.mongabay.com/2023/02/for-some-colombians-vows-of-mining-reform-are-just-a-flash-in-the-pan/
19 Colombia's Evolving Mining Industry: Challenges and Reforms
20 S&P Global Market Intelligence Mining Project.
21 This Act outlines a process for assessing the impact on the environment, health, economy and society of all major projects on Canada federal land. Overview of the Impact Assessment Act
22 Neskantaga First Nation's struggle with Ontario's Ring of Fire mining plans. CBC News. Retrieved from https://www.cbc.ca/news/canada/toronto/ont-ring-of-fire-1.6991468
23 Environmental, social, and governance best practices applied to mining operations. Centre for Strategic and International Studies. https://www.csis.org/analysis/environmental-social-and governance-best-practices-applied-mining-operations

prepared governments are for mine closures. This survey, along with previous assessments, revealed that while governments recognize the importance of mine closure and post-mining transitions, many lack the necessary policies, regulations, enforcement and capacity to manage these processes effectively[24].

Therefore, governments can build engineering capacity for safe and sustainable mining by ensuring there are diverse engineering perspectives and expertise in the government agencies overseeing the mining industry. Governments can leverage this expertise to ensure that codes and policies and the enforcement of the codes are keeping pace with the need for critical minerals while balancing the need for social and environmental protection.

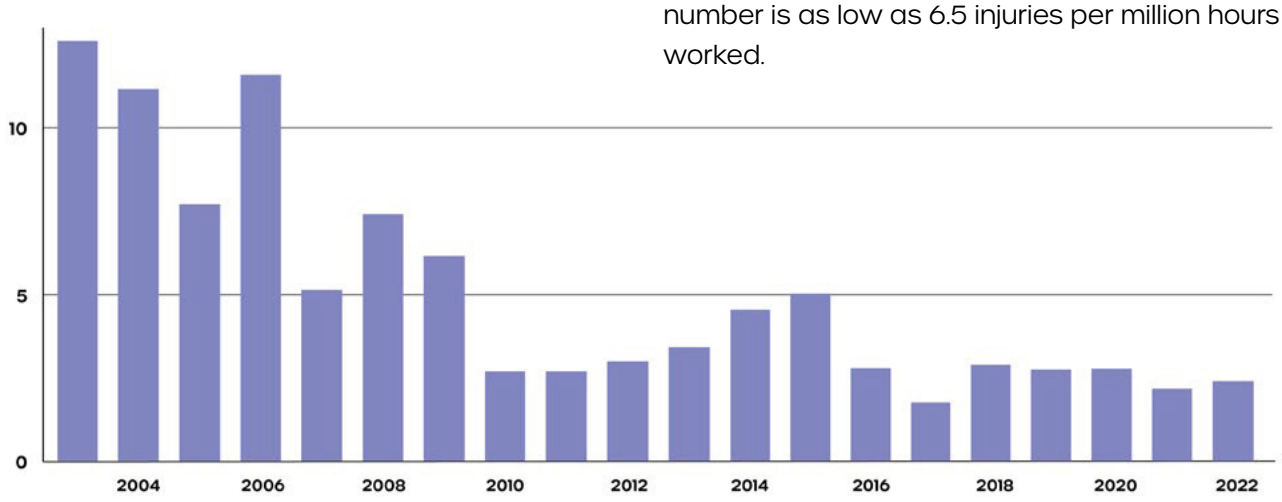
Engineering industry

Mining companies must take ownership and responsibility for the potential impacts of their operations. Many do this by adopting a governance structure and company culture that values safer and more sustainable mining practices across all aspects of operations including in recruitment and training, maintenance of equipment, how incidents are reported and how report results are addressed, and the incorporation of long-term environmental planning into site management.

These and other practices, bolstered by increased global awareness, have increased safety in mining, albeit to varying degrees across regions.

The figure below illustrates nearly a decade of improvement in mining safety within Australia by tracking mining fatalities.[25] In 2022 there were only 3.4 fatalities per 100,000 workers. Although there was a slight uptick in serious injuries, the number is as low as 6.5 injuries per million hours worked.

Figure 2: Deaths in Australian mining

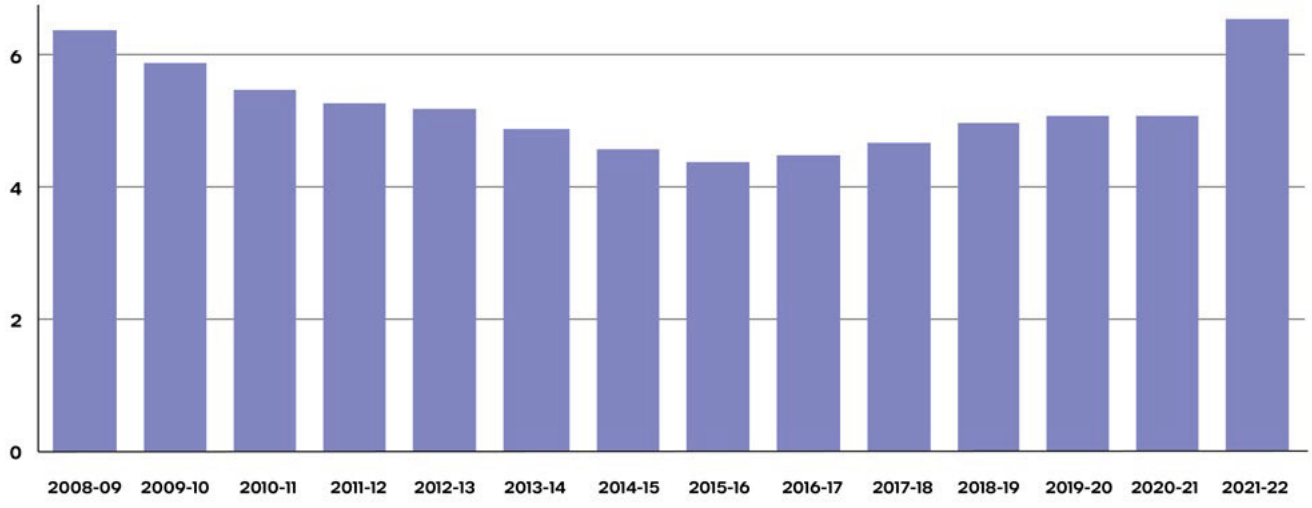


Annual number of fatalities per 100,000 workers in the mining industry. Source: Safe Work Australia.

24 Current status of mine closure readiness: Are governments prepared? https://www.iisd.org/system/files/2021-08/status-mine-closure-readiness-en.pdf

25 How safe are Australia's mines? New analysis shows reform has been stalled for a decade, The Conversation, published online: March 18, 2024

Figure 3: Serious injuries in Australian mining



Annual number of serious injury claims to Safe Work Australia per million hours worked.

However, maintaining and further improving these standards requires ongoing collaboration between government, industry, professional engineers and wider stakeholders. As demonstrated in the example of Chile, government can support industry in this by providing important incentives and regulation, as well as oversight and enforcement, to guide the adoption of safer and more sustainable practices. The mining industry also has a role in keeping up with and investing in advances in technology to provide engineers with the best tools, technologies and resources, as well as training opportunities, to increase efficiency, safety and sustainability in mining operations.

Particular technological challenges which currently require investment from the mining industry to increase safety and sustainability include:

- Electrification of mining-related vehicles and plant equipment, such as rock crushers, which are currently largely fossil fuel driven and contribute large amounts of greenhouse gas emissions.[26 27]
- Reducing water usage, particularly of materials extracted from aquifers, as is the case for many lithium resources. This includes improvement in Direct Extraction methods which can displace solar evaporation technologies.[28]
- Addressing short- and long-term tailing storage, mitigating the environmental impact of polluting and radioactive waste.[29]

26 https://www.mdpi.com/2673-6489/3/1/1
27 https://www.sciencedirect.com/science/article/pii/S2212827116307168
28 https://raeng.org.uk/media/kdynduhd/critical-materials-report.pdf
29 Chapter 12: The Ethics of Rare Earth Elements Over Time and Space. Martin, A. & Iles, A. 2021. Ethics of Chemistry.

In addition to investing in new technologies that can improve safety and better protect the environment, companies need to invest even more in employee training. Not only is training on safety protocols and emergency response needed, with regular drills to help employees retain the information, but the International Labour Organisation notes that mining employees should also be trained on risk assessment, risk mitigation and risk management.[30] This is already being done by many mining companies and should be implemented at scale.

Finally, industry governance and partnerships are critical for helping build a culture of safety in each mining company. The International Council on Mining and Metals (ICMM) convenes leading mining and metals companies and is at the forefront of promoting sustainable development and responsible mining practices. Another governance initiative that includes partnerships is the Initiative for Responsible Mining Assurance (IRMA), an organization that sets standards for responsible mining practices. It provides independent, thirdparty assessment of industrial-scale mine sites. While many mining companies report risks at the company level, IRMA's framework looks at the asset level ensuring they meet high environmental, social and governance (ESG) criteria.[31] IRMA aims to improve mining practices globally by collaborating with mining companies, purchasing companies, NGOs, communities, and labour organizations. This collaboration helps protect the rights and quality of life of workers and their communities, as well as the environment.[32] There are other organisations both at the national and international levels that include promoting safeand sustainable mining as part of their mission and mandate. However, governance must be put into effective action. As the ECI 2024 framework highlights, effective action requires industry associations to provide governance and guidance to the industry it represents to help build a culture of safety that includes ethical operations.

30 Mine safety training: A brief introduction. SafetyCulture. https://safetyculture.com/ topics/mining-safety/mine-safety-training

31 Governance and human rights in mining. Deloitte Insights. https://www2.deloitte.com/us/en/insights/industry/mining-and-metals/tracking-the-trends/2021/strengthen-governance-and-human-rights-in-mining.html

32 https://responsiblemining.net

Conclusion

Achieving safe and sustainable mining practices is a crucial part of delivering a just energy transition, which also safeguards the environment and local communities. It is a collective responsibility that requires the collaboration of engineers, governments, mining companies and communities. Engineers in particular have a vital role to play. They bring the technology, technical knowledge and skills that can help improve the safety and sustainability of mining operations. They also bring soft skills like systems thinking which can support different stakeholders to come together to look more critically at mining's position within the global system and its multifaceted benefits and risks.

The framework of the ECI 2024 highlights the interdependence of the stakeholder groups to build engineering capacity. Safe and sustainable mining activities require professional engineers with technical skills and training to design equipment and processes that can minimize harm to people and the planet. It requires governments to incentivise and importantly enforce sustainable, safe and equitable practices on mining activities. The industry meanwhile must adopt the highest levels of ethical, safe and sustainable practices, and invest in new technology and innovation to reduce environmental damage and increase the safety, sustainability and community benefit of current and future mining operations. Ensuring effective communication between all stakeholders – a systems perspective – particularly including affected communities, is also essential for delivering the benefits of mining to all affected communities and minimising negative impacts.