



## LIFE CYCLE ASSESSMENT AS A TOOL IN SUSTAINABLE MINING FOR IDENTIFYING KEY IMPACT STAGES

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**Abstract:** *This study examines the application of Life Cycle Assessment (LCA) as a decision-support tool for sustainable mining, with a focus on identifying key environmental impact stages across the mining life cycle. A structured, screening-level LCA approach is developed to support early-stage evaluation, incorporating the main phases of mining operations, including resource extraction, material handling, and processing. The proposed approach considers key factors influencing environmental performance and provides a systematic basis for identifying environmental hotspots by determining the stages that contribute most significantly to selected impact categories. It also distinguishes between its application to new mining projects, where data availability is limited and uncertainty is higher, and existing operations, where more detailed information may be available for analysis. The results indicate that even at a preliminary level, this approach can effectively highlight stages with significant environmental contributions, supporting the prioritization of processes for further investigation. The findings suggest that integrating such a structured LCA framework into early project development can improve the consistency of environmental evaluations and support more informed decision-making, while also providing a basis for subsequent, site-specific assessments.*

**Keywords:** *Life Cycle Assessment (LCA), Sustainable Mining, Hotspot Analysis, Resource Efficiency, Mining Life Cycle, Impact Assessment*

### 1. Current state of research on LCA in mining

Life Cycle Assessment (LCA) has become a fundamental methodological framework for evaluating the environmental performance of mining systems, particularly in the context of increasing environmental regulation, sustainability reporting, and the growing demand for critical raw materials. This approach enables the systematic quantification of environmental impacts across the entire life cycle of mineral production, from extraction and beneficiation to processing and, in some cases, downstream use and end-of-life stages. Its methodological foundation is defined by the ISO 14040 and ISO 14044 standards developed by the scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation [1], [2].

The application of this framework within the mining industry has evolved significantly over recent decades. Early studies demonstrated its feasibility for mining systems while also highlighting key challenges, including limited data availability, difficulties in defining system boundaries, and overall methodological complexity [3]. Systematic reviews indicate that this methodology is now widely applied to evaluate the environmental footprint of metals and mineral production, with growing methodological sophistication and expanded system boundaries [4], [5].

Despite these advancements, a major challenge remains the lack of methodological harmonization. Differences in functional units, system boundaries, allocation procedures, and impact assessment methods limit comparability across studies. Santero N. and Hendry J. [6] emphasize the need for harmonized approaches

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tailored specifically to the metals and mining sector, particularly regarding co-product allocation and consistent selection of impact categories. This issue is further complicated by the inherent complexity of mining systems, including polymetallic ore bodies and site-specific operational conditions.

Recent developments also highlight a diversification of methodological approaches. Di Bari et al. [7] note the increasing fragmentation of practices and propose a framework to systematize them using text-mining techniques, reflecting a shift toward more structured and data-driven classification. At the same time, there is a growing trend toward integrating this analytical approach with other quantitative sustainability assessment tools. Cerchione et al. [8] demonstrate that combining it with complementary methods improves the robustness of sustainability evaluations, thereby supporting more informed decision-making in complex industrial systems such as mining.

From an environmental performance perspective, studies consistently identify energy consumption as a primary driver of impacts within mining operations. Energy-intensive processes, particularly comminution and mineral processing, contribute significantly to global warming potential and other environmental impact categories [4]. In addition, the overall environmental profile of mining activities is strongly influenced by factors such as ore grade, energy sources, and processing technologies. A comprehensive synthesis by Nuss and Eckelman [8] highlights substantial variability in impacts across different metals, underscoring the importance of material-specific assessments.

Beyond purely environmental considerations, increasing attention is being given to the integration of social and economic dimensions within life cycle-based frameworks. Ionce and Breabăn [9] present a combined approach incorporating both environmental assessment and Social Return on Investment (S-ROI), applied to mining in Romania, demonstrating how environmental and socio-economic impacts can be evaluated simultaneously. This direction aligns with the broader concept of Life Cycle Sustainability Assessment (LCSA), which seeks to integrate environmental, social, and economic aspects into a unified analytical framework.

Despite significant progress, several limitations persist. Data availability and quality remain major constraints, as mining operations frequently rely on site-specific and proprietary datasets that are not publicly accessible. This lack of transparency introduces uncertainty and limits the reproducibility of results. Furthermore, the variability of geological conditions and mining methods complicates the development of standardized models. Recent reviews also highlight the need to improve the representation of certain impact categories, particularly biodiversity and land use, which are often insufficiently addressed in current methodologies [5].

Overall, the literature indicates that Life Cycle Assessment has evolved into a mature and increasingly sophisticated tool for evaluating the environmental performance of mining systems. Its capacity to systematically quantify impacts across complex value chains makes it particularly valuable in a sector characterized by high energy intensity, site-specific variability, and growing regulatory pressure. However, despite these advances, several critical challenges continue to limit its full potential as a decision-support instrument.

A primary area requiring further development is methodological harmonization. The continued use of divergent functional units, system boundaries, allocation rules, and impact assessment methods undermines the comparability and consistency of results across studies. Establishing sector-specific guidelines and standardized methodological frameworks would significantly enhance the reliability and usability of assessments, particularly for benchmarking and policy-making purposes. In this context, greater alignment with international standards and the development of mining-specific product category rules could represent an important step forward.

Equally important is the improvement of data quality, transparency, and accessibility. Mining systems rely heavily on site-specific operational data, much of which remains proprietary or insufficiently documented. This introduces uncertainty and limits reproducibility, ultimately affecting the credibility of results. Expanding high-quality, publicly available life cycle inventory databases tailored to mining processes, along with the adoption of digital tools for real-time data collection and reporting, could substantially improve the robustness of future analyses.

Another critical direction involves the more comprehensive integration of sustainability dimensions beyond environmental impacts. While environmental assessment remains the core strength of the methodology, there is a growing need to incorporate social and economic considerations in a consistent and quantifiable manner. The advancement of Life Cycle Sustainability Assessment (LCSA), as well as hybrid approaches combining environmental analysis with indicators such as social risk, economic value, and circularity, offers a promising pathway toward more holistic evaluations.

Furthermore, emerging challenges such as biodiversity loss, land use transformation, and resource depletion require more refined and context-sensitive impact assessment models. Current methodologies often provide limited or generalized representations of these aspects, which are particularly relevant in mining activities. Advancing impact characterization models and incorporating spatially explicit assessments will be essential to better capture the true environmental footprint of mining operations.

Finally, the role of this methodology in supporting strategic decision-making is expected to expand in the context of the global transition toward low-carbon and resource-efficient economies. As demand for critical raw materials increases, decision-makers will require more robust, transparent, and comparable tools to evaluate trade-offs between environmental impacts, economic benefits, and supply security. Strengthening the integration of life cycle-based approaches into policy frameworks, corporate strategies, and investment decisions will therefore be crucial.

In conclusion, while Life Cycle Assessment has reached a high level of methodological maturity, its continued evolution will depend on improved standardization, enhanced data infrastructures, and deeper integration with broader sustainability frameworks. Addressing these challenges will be essential for ensuring that it can effectively guide responsible and sustainable development within the mining sector.

## 2. Proposed methodology

The proposed methodology, referred to as HIT-Mine (Hotspot Identification Tool for Mining Systems), is a screening-level Life Cycle Assessment (LCA) framework developed to identify environmental hotspots across mining technological flows. The approach is designed to support both early-stage project evaluation and the assessment of existing mining operations with historical environmental impacts. The method is aligned with the principles of ISO 14040 and ISO 14044, ensuring consistency with internationally recognized LCA practices, while introducing a simplified structure adapted to the constraints of the mining sector. In addition, the approach incorporates the Planetary Boundaries concept introduced by Johan Rockström [10] and further developed by Will Steffen [11], enabling the interpretation of environmental impacts in relation to global sustainability limits.

Unlike conventional LCA methodologies that rely on detailed life cycle inventories and characterization models, this approach adopts a semi-quantitative structure. This allows for the integration of heterogeneous data sources, including measured values, estimated parameters, and literature-based information, while maintaining methodological transparency.

The methodology is structured as a sequential process that enables:

- the consistent definition of mining system boundaries,
- the evaluation of environmental pressures across key impact categories,
- the identification of critical processes contributing disproportionately to overall environmental impact.

This structure ensures that the method remains both scientifically grounded and operationally applicable, facilitating its use as a decision-support tool in mining sustainability assessments.

In Figure 1, is presented the structured decision chart of the HIT-Mine methodology, illustrating the step-by-step process for identifying environmental hotspots in mining systems. The scheme outlines the sequence of actions, required input data, and corresponding outputs, providing a clear operational pathway from goal definition to decision support.

The decision chart provides a structured and sequential pathway for applying the proposed methodology in a consistent and transparent manner. It can be used as an operational framework to guide the assessment from the initial definition of the system to the identification of environmental hotspots and the derivation of decision-support outputs.

The process begins with the definition of the assessment objective, which establishes whether the analysis is intended for screening, comparison of technological alternatives, or the identification of improvement measures. This initial step determines the level of detail required and influences the depth of subsequent data collection and analysis.

Following this, the mining context is defined by specifying the type of operation, the life cycle stage, and the commodity of interest. This step ensures that the assessment is properly framed and that subsequent assumptions and data selections remain consistent with the characteristics of the system under study.

The definition of system boundaries represents a critical step, as it determines which processes are included in the assessment. Depending on the objective and data availability, the system may be limited to extraction, extended to include processing, or expanded to cover the full technological chain, including waste management and closure. The inclusion of infrastructure and energy supply is considered where these elements represent a significant contribution to the overall environmental performance.

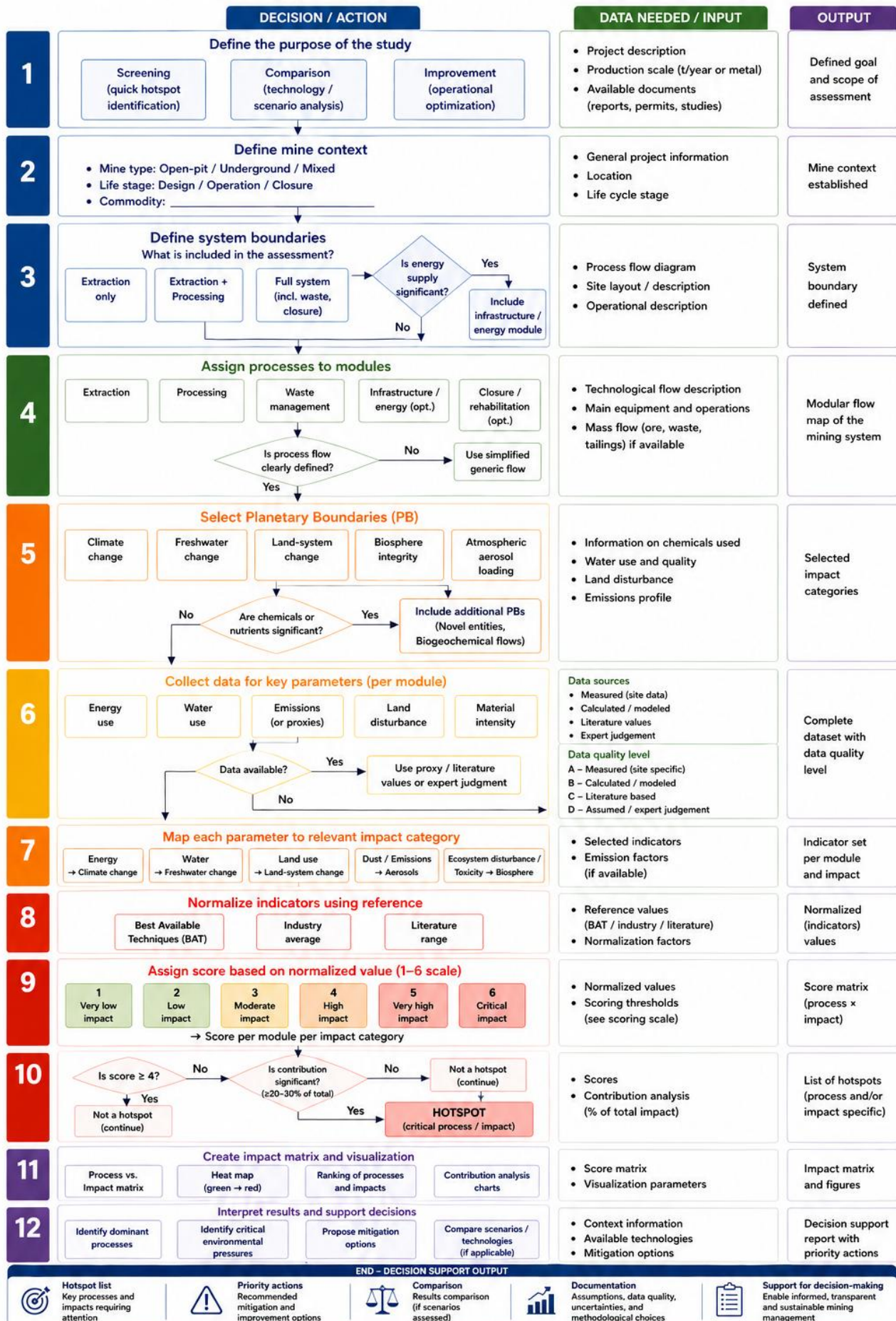


Fig. 1. Decision chart for the application of the HIT-Mine methodology

Once the boundaries are established, the technological flow is structured into modules. This modularization enables the separation of the system into distinct components, such as extraction, processing, and waste management, with optional inclusion of supporting systems. In cases where detailed process information is not available, the methodology allows the use of simplified generic flows, ensuring applicability under data-limited conditions.

The selection of environmental impact categories is then performed based on the relevance of the Planetary Boundaries framework to mining activities. A core set of impact categories is typically considered, while additional categories may be included where site-specific conditions justify their relevance. This step ensures that the assessment focuses on the most significant environmental pressures associated with the system.

The subsequent stage involves the collection and organization of input data for each module. The methodology accommodates multiple data sources, including measured values, calculated estimates, literature data, and expert judgment. Each data point is associated with a qualitative data quality level, which supports transparency and facilitates the interpretation of results.

The collected data are then translated into impact indicators by linking each parameter to its corresponding environmental category. These indicators are normalized using reference values derived from industry benchmarks, literature ranges, or best available techniques, allowing the results to be expressed on a comparable basis.

A semi-quantitative scoring procedure is subsequently applied, assigning values on a scale from 1 to 6 to reflect the relative magnitude of environmental pressure. This scoring system enables the aggregation of results and supports the identification of differences between processes and impact categories.

Hotspot identification is carried out through a combined evaluation of impact intensity and relative contribution. Processes that exhibit elevated scores and represent a significant share of the total impact are classified as critical elements within the system. This step allows the differentiation between dominant environmental pressures and secondary effects.

The results are then organized into a structured matrix and visualized to facilitate interpretation. This representation enables the identification of patterns across processes and impact categories, supporting a clear understanding of system behavior.

In the final stage, the results are interpreted in relation to the initial objective of the assessment. This includes the identification of priority areas for intervention, the evaluation of potential mitigation measures, and, where applicable, the comparison of alternative technological configurations. The overall process supports informed decision-making by providing a transparent and systematic basis for evaluating environmental performance within mining systems.

### 3. Case study

The purpose of this comparative analysis is to demonstrate the applicability of the proposed methodology under two distinct conditions: an existing mining operation and a project-level mining system. By applying the same methodological framework to both cases, the analysis highlights the capacity of the approach to function across different stages of the mining life cycle and under varying levels of data availability.

The comparison is intended to illustrate how environmental hotspots can be identified using both measured data, typically available for operational sites, and estimated or literature-based data, which are characteristic of early-stage projects. In this context, the analysis also provides insight into how uncertainty, data quality, and system definition influence the interpretation of results.

Furthermore, the comparative approach enables the evaluation of differences in environmental performance between an established technological system and a conceptual design. This allows the identification of improvement opportunities in existing operations, as well as the anticipation of potential environmental pressures at the project development stage.

It is important to note that the two case studies differ in mining method, representing an open-pit operational system and an underground project design. As such, they do not constitute directly equivalent systems in terms of geological conditions or technological configuration. The objective of the comparison is therefore not to establish absolute performance superiority, but to assess the ability of the methodology to consistently identify environmental hotspots across different mining approaches. This distinction reflects real-world conditions, where the choice of mining method is constrained by deposit characteristics and economic considerations.

Overall, the analysis aims to demonstrate that the methodology can support decision-making in both retrospective assessments and prospective planning scenarios, while remaining adaptable to different technological contexts.

### **3.1. Existing mine - conventional operational system**

The first case study is represented by the Escondida mine, one of the largest copper-producing operations globally [12]. The mine is characterized by large-scale open-pit extraction and conventional processing technologies, including drilling and blasting, truck-and-shovel material handling, and ore beneficiation through crushing, grinding, and flotation [12], [13].

The operation relies significantly on diesel-powered mobile equipment and grid-based electricity, resulting in substantial energy demand. Water consumption is also considerable due to the requirements of mineral processing, while tailings are managed in large-scale storage facilities [13]. These characteristics make the system representative of current industrial copper mining practices.

The selection of this case is supported by the availability of publicly reported operational data provided by BHP and other industry sources [12], [13]. These data enable the characterization of key environmental parameters, including energy use, water consumption, and emissions, allowing for a realistic application of the methodology [13], [14].

### **3.2. Project - level mine**

The second case study corresponds to the Kutcho Project, a mining project developed with a strong focus on environmental performance and reduced operational impacts [15], [16]. The project is designed as an underground operation with a comparatively smaller surface footprint and incorporates several technological measures aimed at minimizing environmental pressures.

Key features of the project include the use of electrified mining equipment, reliance on low-carbon energy sources, and the implementation of dry stack tailings, which significantly reduces water consumption and the risks associated with conventional tailings storage facilities [15], [17]. In addition, the project emphasizes efficient resource use and reduced waste generation [16].

Due to its development stage, the available data are primarily derived from feasibility studies, technical reports, and company disclosures [15], [16], [17]. As such, the dataset reflects estimated parameters rather than measured values. However, these data are sufficiently detailed to allow the application of the methodology and to evaluate the potential environmental performance of the system.

The inclusion of this case enables the assessment of how the proposed methodology performs in a prospective context and whether it can effectively capture the environmental benefits associated with sustainability-oriented mine design [15], [16].

### **3.3. Application of the methodology**

The proposed methodology was applied to both case studies following the sequence defined in the decision chart. The same procedure was used for each system, allowing the evaluation of environmental pressures under different technological configurations and levels of data availability.

The application starts with the definition of system boundaries and the organization of mining activities into extraction, processing, and waste management. Available data for each process are then compiled and linked to the selected impact categories. These inputs are translated into indicators, normalized using reference values, and evaluated through the semi-quantitative scoring system.

The resulting scores provide a basis for identifying processes associated with higher environmental pressure and for examining how impacts are distributed across the technological flow. This approach allows the comparison of results between the operational system and the project-level scenario.

#### ***System definition and boundaries***

The system is described through the flow of material and energy between the main process stages. Ore extraction generates two primary outputs: ore directed to processing and waste rock sent to disposal. During processing, the ore is transformed into concentrate, while the remaining material is discharged as tailings. These flows define the overall structure of the system and allow the allocation of inputs and environmental pressures to each stage.

The assessment is expressed in relation to a reference flow corresponding to the production of copper concentrate. For the operational case, this reference is based on reported production data. For the project-level case, it is derived from estimated production capacity. This approach allows the results to be interpreted on a comparable basis, even when absolute production levels differ.

The system is modeled at the process level, where each module represents an aggregation of unit operations. Individual equipment or subprocesses are not assessed separately; instead, their effects are represented through aggregated indicators such as total energy use, water consumption, and emissions.

Some simplifications are applied in order to maintain the screening-level character of the methodology [18]. Variations in ore grade, temporal changes in operation, and detailed process efficiencies are not explicitly modeled. Instead, average or representative values are used. These simplifications allow the method to be applied under conditions of limited data availability while retaining the main characteristics of each system.

The two case studies differ in mining method, operational scale, and technological configuration. Open-pit extraction is associated with large-scale material movement and surface disturbance, while underground mining involves different energy requirements and a comparatively smaller surface footprint. These differences are reflected in the distribution of environmental pressures across the system.

The assessment does not aim to establish direct equivalence between the two systems. Instead, it examines how environmental pressures are distributed within each system and how the methodology captures these patterns. This supports the identification of dominant processes and enables the comparison of environmental hotspot profiles between the two case studies.

#### *Impact category selection (Planetary Boundaries applied to the case study)*

The assessment is based on environmental impact categories derived from the Planetary Boundaries framework [10], [11]. In principle, all planetary boundaries can be considered within the methodology, depending on the scope of the assessment and the level of detail required.

For the present analysis, a selection of five impact categories was made in order to demonstrate how the screening approach can be applied in practice. The selection focuses on categories that are directly influenced by mining activities and that allow a clear linkage between process parameters and environmental pressures.

The following categories were included:

- Climate Change, associated with greenhouse gas emissions resulting from fuel consumption and electricity use across extraction and processing stages.
- Freshwater Change, reflecting water consumption and interactions during mineral processing and waste management.
- Land-System Change, related to land occupation and transformation caused by mining activities and the development of waste storage facilities.
- Biosphere Integrity, representing the effects of land disturbance and emissions on ecosystems and biodiversity.
- Atmospheric Aerosol Loading, linked to dust and particulate emissions generated during drilling, blasting, hauling, and material handling.

These categories are used to illustrate the application of the methodology and the identification of environmental hotspots within the technological system. The selection does not limit the methodology, as additional planetary boundaries, such as ocean acidification, stratospheric ozone depletion, biogeochemical flows, or novel entities, can be incorporated when required by the scope of the assessment.

#### *Data collection and input parameters*

The application of the methodology is based on the collection of input data describing the main characteristics of each process within the defined system boundaries. The data are organized according to the three process modules: extraction, processing, and waste management.

For each module, a set of key parameters is defined in order to represent the main environmental drivers associated with mining activities. These parameters include:

- Energy consumption, expressed through fuel use and electricity demand.
- Water use, including process water requirements and water management practices.
- Material intensity, such as ore grade and the ratio between ore and waste.
- Land disturbance, reflecting the extent of surface occupation and transformation.
- Emissions or emission proxies, associated with energy use and material handling.

These parameters are selected because they can be directly associated with the selected impact categories and can be obtained or approximated for both operational and project-level systems.

For the Escondida operation, input data are derived from publicly available reports, including sustainability disclosures and technical documentation [12], [13], [14]. These data provide information on operational performance, particularly in terms of energy consumption, water use, and production scale [12], [13]. Where specific values are not explicitly reported, representative values from industry benchmarks are used to complete the dataset.

For the Kutcho Project, input data are obtained from feasibility studies and project documentation [15], [16], [17]. These data represent expected operational parameters and include information on planned energy

use, water management strategies, and processing configuration. The use of electrified equipment and dry stack tailings is reflected in the corresponding input parameters [15], [16].

All input data are organized at the level of process modules, allowing a direct link between technological stages and environmental pressures. This structure enables the subsequent translation of input parameters into impact indicators and supports the comparison between the two case studies. The use of aggregated process-level parameters is consistent with the screening-level character of the methodology and supports rapid comparative assessment under conditions of limited data availability.

### Scoring system

The normalized indicators are translated into impact scores using a semi-quantitative scale ranging from 1 to 6. The purpose of this step is to express the relative intensity of environmental pressure in a form that allows direct comparison between processes and impact categories.

The scoring is based on the position of each normalized indicator in relation to the reference range defined by the selected benchmarks. Lower values, closer to best available practice, correspond to lower scores, while higher values, approaching or exceeding typical upper ranges, correspond to higher scores.

The scale is defined as follows:

- 1 - Very Low Impact: performance close to best available conditions, with minimal environmental pressure
- 2 - Low Impact: limited impact, within typical operational ranges
- 3 - Moderate Impact: noticeable impact, approaching higher ranges of sector performance
- 4 - High Impact: significant environmental pressure compared to reference values
- 5 - Very High Impact: strong deviation from reference conditions, indicating substantial impact
- 6 - Critical Impact: extreme values, indicating very high environmental pressure

Scores are assigned at the level of each process module and impact category, allowing the identification of variations across the technological flow. The use of a fixed scale ensures that the evaluation remains consistent, even when different types of data or units are involved.

The scoring system does not aim to provide absolute quantification of environmental impacts, but rather to establish a relative ranking of processes based on their contribution to environmental pressure. This allows the identification of priority areas within the system and supports the subsequent hotspot analysis.

The assignment of screening scores is based on the relative deviation between the observed process value and the corresponding Best Available Techniques (BAT) reference value. This ratio-based approach allows the comparison of different environmental parameters using a common interpretation scale. Higher ratios indicate increasing environmental pressure relative to optimized operational conditions, while lower ratios reflect performance closer to best available practices. The scoring intervals used in the assessment are presented in Table 1.

*Table 1. Screening score classification based on the ratio between observed values and BAT reference conditions*

| <b>Ratio (Observed Value / BAT Reference)</b> | <b>Screening Score</b> | <b>Impact Level</b> | <b>Interpretation</b>                                                                                                                     |
|-----------------------------------------------|------------------------|---------------------|-------------------------------------------------------------------------------------------------------------------------------------------|
| ≤ 1.0                                         | 1                      | Very Low            | Process performance is equivalent to or better than BAT conditions, indicating minimal environmental pressure.                            |
| 1.0 - 1.5                                     | 2                      | Low                 | Slight deviation from BAT values, with limited environmental impact.                                                                      |
| 1.5 - 2.0                                     | 3                      | Moderate            | Noticeable environmental pressure, approaching the upper range of optimized operational performance.                                      |
| 2.0 - 3.0                                     | 4                      | High                | Significant deviation from BAT conditions, indicating increased environmental impact.                                                     |
| 3.0 - 5.0                                     | 5                      | Very High           | Strong environmental pressure compared to reference conditions, requiring mitigation measures.                                            |
| > 5.0                                         | 6                      | Critical            | Extreme deviation from BAT values, associated with critical environmental pressure and potential exceedance of sustainability thresholds. |

The scoring table provides the basis for translating quantitative process parameters into comparable environmental impact levels within the screening methodology. The ratio between the observed value and the corresponding Best Available Techniques (BAT) reference value expresses the relative deviation of a process from optimized operational conditions. Lower ratios indicate performance closer to best available practices, while higher ratios reflect increasing environmental pressure.

The use of ratio intervals allows the integration of parameters expressed in different units into a common evaluation framework [18]. In this way, energy consumption, emissions, water use, and land occupation can be interpreted using the same scoring structure. The assigned screening scores therefore represent the relative intensity of environmental pressure rather than an absolute quantification of impact.

The interpretation of the scores also considers the operational and environmental context of the assessed system. For example, a moderate deviation from BAT values may receive a higher screening score when associated with environmentally sensitive regions, such as areas affected by water scarcity or ecosystem vulnerability. This approach allows the methodology to combine benchmark-based evaluation with site-specific environmental considerations during hotspot identification.

Table 2 presents the application of the proposed screening methodology to the selected case studies through the comparison of operational parameters with technology-specific BAT reference values. The table integrates process-level data, associated planetary boundary categories, and the assigned screening scores, providing the basis for the identification of environmental hotspots within each mining system.

*Table 2. Screening-level assessment parameters, technology-specific BAT reference values, and assigned impact scores for the selected case studies*

| Process Stage    | Parameter                     | Unit                           | Escondida (Open Pit) | BAT - Open Pit     | Kutcho Project (Underground) | BAT - Underground  | PB Category                              | Assigned Screening Score (E/K) | Reference Document (BAT)                                                    |
|------------------|-------------------------------|--------------------------------|----------------------|--------------------|------------------------------|--------------------|------------------------------------------|--------------------------------|-----------------------------------------------------------------------------|
| Extraction       | Energy (Diesel / Electricity) | MJ / t ore                     | 120                  | 75                 | 45                           | 35                 | Climate Change                           | 3 / 2                          | BREF Energy Efficiency (ENE) [19]                                           |
|                  | GHG Emissions                 | kg CO <sub>2</sub> -eq / t ore | 10.5                 | 6.0                | 2.2                          | 2.0                | Climate Change                           | 3 / 2                          | BREF Energy Efficiency (ENE) [19]                                           |
|                  | Dust Emissions (PM)           | kg PM / t ore                  | 0.25                 | 0.10               | 0.10                         | 0.05               | Atmospheric Aerosol Loading              | 4 / 3                          | BREF Management of Tailings and Waste-Rock in Mining Activities (MTWR) [20] |
| Processing       | Electricity Demand            | kWh / t ore                    | 35                   | 25                 | 26                           | 18                 | Climate Change                           | 2 / 2                          | BREF Non-Ferrous Metals Industries (NFM) [21]                               |
|                  | Water Use                     | m <sup>3</sup> / t ore         | 0.75                 | 0.45               | 0.40                         | 0.25               | Freshwater Change                        | 6 / 2                          | BREF Industrial Cooling Systems (ICS) [22]                                  |
| Waste Management | Tailings System Type          | –                              | Conventional slurry  | Thickened tailings | Dry stack tailings           | Dry stack tailings | Freshwater Change                        | 5 / 2                          | BREF Management of Waste from Extractive Industries (MWEI) [23]             |
|                  | Water Loss                    | m <sup>3</sup> / t ore         | 0.45                 | 0.25               | 0.12                         | 0.05               | Freshwater Change                        | 3 / 2                          | BREF MWEI [23]                                                              |
|                  | Land Occupation               | m <sup>2</sup> / t ore         | 3.5                  | 1.5                | 0.8                          | 0.5                | Land-System Change / Biosphere Integrity | 5 / 2                          | BREF MWEI - Management Plan [23]                                            |

The comparative assessment highlights a clear contrast between the environmental profiles of the two analyzed mining systems. The operational open-pit configuration exhibits higher environmental pressure across most categories, while the project-level underground configuration remains generally closer to BAT conditions due to the integration of lower-impact technological solutions.

The extraction stage is primarily influenced by the intensity of material movement and the associated fuel consumption. The higher scores observed for the open-pit system reflect the operational requirements of large-scale haulage and surface excavation activities, which contribute directly to increased energy demand, greenhouse gas emissions, and atmospheric particulate generation. In comparison, the underground configuration benefits from reduced surface operations and lower overall material displacement, resulting in lower environmental pressure within the extraction stage.

Within the processing stage, electricity demand remains significant for both systems due to the energy-intensive nature of comminution and flotation processes [21]. Freshwater use emerges as one of the dominant environmental pressures identified in the assessment. Although the ratio between observed water consumption and BAT reference values would correspond to a moderate screening score, the final score assigned to the operational system was adjusted to reflect the environmental conditions specific to the site. The Escondida operation is located in northern Chile, a region characterized by severe water stress and limited freshwater availability. Under these conditions, water consumption represents a substantially amplified environmental pressure, justifying the assignment of a higher screening score. This adjustment illustrates how the methodology incorporates site-specific environmental sensitivity during the interpretation stage of the assessment.

A similar contextual interpretation was applied to land occupation within the open-pit system. While the ratio between the observed land occupation and BAT reference values indicates a high impact level, the final score also reflects the large-scale and long-term surface transformation associated with open-pit extraction and tailings storage [20], [23]. The extensive alteration of land surfaces and ecosystem fragmentation associated with these activities increases the environmental significance of land-system change and biosphere integrity impacts beyond the numerical BAT deviation alone.

The waste management stage represents the most pronounced difference between the two systems. Conventional slurry tailings management is associated with increased water losses, larger land occupation, and extended long-term environmental management requirements. These factors contribute significantly to the impact categories related to freshwater change, land-system change, and biosphere integrity. The implementation of dry stack tailings within the project-level system substantially reduces water losses and limits the spatial footprint of waste storage infrastructure, resulting in lower impact scores across these categories [15], [16].

Overall, the results indicate that the proposed methodology successfully identifies the stages of the technological flow associated with elevated environmental pressure and differentiates between mining systems characterized by distinct technological configurations. The assessment identifies water use, land occupation, and waste management as the dominant hotspots within the conventional mining system, while the project-level configuration demonstrates improved environmental performance through the integration of lower-impact operational strategies and reduced environmental disturbance.

### **3.4. Methodological considerations and limitations**

The proposed methodology is designed as a screening-level assessment tool intended to support the early identification of environmental hotspots within mining systems. The approach focuses on the relative evaluation of environmental pressures associated with the main stages of the technological flow and is therefore suited for comparative analysis, preliminary sustainability evaluation, and decision-support applications [1], [2], [18].

Unlike conventional Life Cycle Assessment methodologies based on detailed inventories and quantitative impact characterization, the present approach adopts a semi-quantitative structure based on process indicators, BAT reference values, and contextual interpretation. This allows the methodology to be applied in situations where complete operational datasets are unavailable or where rapid environmental screening is required, such as feasibility studies, strategic planning, or comparative technology assessment.

The methodology does not aim to replace a full quantitative LCA [18]. Instead, it provides a simplified framework capable of identifying the stages and processes associated with elevated environmental pressure, thereby supporting the prioritization of detailed investigations and mitigation strategies. The use of BAT reference values enables the evaluation of process performance relative to achievable operational conditions within the mining sector, while the integration of contextual interpretation allows the assessment to reflect site-specific environmental sensitivity.

Certain impact scores may therefore incorporate environmental conditions that extend beyond the direct numerical deviation from BAT values. This is particularly relevant for parameters strongly influenced by regional conditions, such as freshwater use in water-stressed regions or land occupation in systems characterized by extensive surface transformation. The inclusion of such contextual considerations improves the interpretative capacity of the methodology while maintaining the structure of a screening-level assessment.

The framework remains adaptable to different mining systems, commodities, and assessment scopes. Although the present application focuses on selected planetary boundaries [10], [11] relevant to mining activities, the methodology allows the integration of additional environmental categories where required by the characteristics of the analyzed system or by the objectives of the assessment.

#### 4. Conclusions

The present study proposed a screening-level methodology for the identification of environmental hotspots within mining technological systems through the integration of Life Cycle Assessment principles, Planetary Boundaries, and BAT-based benchmarking. The developed framework enables the evaluation of environmental pressures associated with the main stages of mining activities, namely extraction, processing, and waste management, using a semi-quantitative scoring approach adapted to different levels of data availability.

The methodology was applied to two distinct mining configurations represented by an operational large-scale open-pit system and a project-level underground mining system. The comparative analysis demonstrated the capacity of the approach to differentiate between technological configurations and to identify the stages associated with elevated environmental pressure. The results highlighted water use, land occupation, and waste management as the dominant hotspots within the conventional open-pit system, while the project-level configuration exhibited environmental performance closer to BAT conditions due to the integration of lower-impact technological solutions such as underground extraction, electrification, and dry stack tailings.

The proposed framework demonstrates that meaningful environmental interpretation can be achieved at a screening level without the need for fully developed life cycle inventories. By combining operational indicators with BAT reference values and contextual environmental interpretation, the methodology provides a structured approach for evaluating mining systems under both operational and project-development conditions.

An important aspect of the methodology is its adaptability. The framework allows the integration of additional planetary boundaries, different mining methods, and alternative technological configurations depending on the objectives and scope of the assessment. This flexibility supports its application in preliminary project evaluation, comparative technology assessment, sustainability screening, and the prioritization of detailed environmental investigations. The methodology therefore represents a practical decision-support tool capable of bridging the gap between simplified environmental screening and detailed quantitative assessment approaches. Through the integration of process-level analysis, benchmark comparison, and environmental context, the proposed approach contributes to the development of more transparent and operationally applicable sustainability assessment methods for the mining sector.

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