FUTURE OF COMMINUTION WORKSHOP

1. INTRODUCTION

The mining industry is under increasing pressure to reduce energy and water consumption, lower emissions, and improve the sustainability of mineral processing systems. Innovation in comminution technologies will play a critical role in meeting these goals. However, assessing the maturity and readiness of emerging technologies remains complex—particularly in mining, where variability in ore types, processes, and operational constraints can significantly affect adoption outcomes.

This document presents the official report of the “Future of Comminution” Workshop, convened by CEEC International on March 30, 2025, in Cape Town, South Africa. Organized as a high-level technical forum, the workshop gathered over 40 senior professionals from mining companies, OEMs, research institutions, consulting firms, and international NGOs, all participating under Chatham House Rule.

A core feature of the workshop was a facilitated group exercise designed to explore how technologies are perceived and assessed across four thematic dimensions: economics (Capital cost, operating cost and revenue), environmental impact (power consumption, emissions, water and tailings), ability to operate (maintainability, operability and throughput), and technology readiness. This exercise was not intended to produce definitive rankings, but rather served as a structured tool to encourage technical dialogue, test current assumptions, and illuminate key gaps in evaluation frameworks and publicly available information.

This report presents a synthesis of the workshop discussions and insights, aiming to support ongoing industry efforts to develop more robust, transparent, and context-relevant frameworks for assessing technological readiness in mining.

2. CEEC’S MISSION AND ROLE IN THE INDUSTRY

The Coalition for Minerals Efficiency (CEEC International) is a global not-for-profit organization dedicated to accelerating the adoption of eco-efficient mineral and metals production practices. Since its founding, CEEC has been a trusted, neutral platform connecting industry leaders, researchers, and technology providers to advance solutions that reduce energy use, emissions, water consumption, and waste in mining.

Over the past decade, CEEC has established itself as a unique authority in the field of comminution and energy efficiency, thanks to its evidence-based approach, cross-sector collaboration, and commitment to knowledge sharing. CEEC's initiatives – such as the internationally recognized CEEC Medals, the Energy Curves benchmarking tool, and the recently launched Global Water Initiative – reflect a consistent vision: to support the resource sector in delivering essential minerals with minimal environmental impact.

Crucially, CEEC operates independently of commercial agendas. As an NGO, it does not promote or endorse specific technologies or vendors. Instead, it provides a level playing field for critical technical analysis, ensuring that discussions are rooted in sound science, operational insight, and long-term sustainability goals. This neutrality allows CEEC to convene diverse voices and drive the kind of systems-level thinking that the mining sector urgently needs.

In this spirit, CEEC convened the “Future of Comminution” workshop in Cape Town, a high-level technical forum designed to explore which emerging technologies have the greatest potential to enable the mining industry to meet its long-term sustainability targets. This report captures the outcomes of that unique gathering.

3. PURPOSE OF THE WORKSHOP – WHY REIMAGINING COMMINUTION MATTERS

The global push toward decarbonization is driving an unprecedented surge in demand for critical minerals such as copper, lithium, nickel, and rare earth elements. These metals are essential for the energy transition, enabling technologies like electric vehicles, wind turbines, solar panels, and battery storage systems. However, the path to a low-carbon future paradoxically requires a massive expansion of mining and mineral processing activities – a reality that presents both a moral challenge and a technical imperative.

To meet projected demand, the mining industry will need to process increasingly complex and lower-grade ores, often in regions facing water scarcity, energy constraints, and heightened scrutiny from communities and regulators. This means that not only will more rock need to be moved, crushed, ground, and treated – it will need to be done with less energy, less water, and a dramatically smaller environmental footprint.

Comminution – the process of breaking rock into fine particles – sits at the center of this dilemma. It is consistently one of the largest consumers of energy in mineral processing, frequently responsible for more than half of a mine site's total power draw. In addition, it directly affects downstream water use, tailings production, and emissions intensity across the value chain.

Despite its critical importance, the comminution circuit has seen relatively limited innovation in recent decades. Most plants today still operate conventional SABC or SAG-ball configurations, often pushing equipment well beyond its original design capacity. The result is a status quo defined by high operating costs, substantial GHG emissions, and constrained flexibility to adapt to changing orebody characteristics.

In the context of Net Zero goals, this is no longer sustainable.

Reaching carbon neutrality by 2050 – or earlier, as some companies and governments have pledged – will require a fundamental rethink of how minerals are processed. Energy efficiency alone is not enough; the industry must also consider radical innovation, including dry processing, coarse particle liberation, alternative breakage mechanisms, and integration of renewable energy sources. The time to experiment at the margins has passed – the industry now needs step-change solutions, and a clear understanding of which emerging technologies hold the greatest promise.

With this in mind, CEEC convened the “Future of Comminution” workshop in Cape Town as a technical deep-dive into the next generation of breakage technologies. Each group was invited to discuss and share their interpretations, experiences, and observations based on four thematic dimensions: economics (Capital cost, operating cost and revenue), environmental impact (power consumption, emissions, water and tailings), ability to operate (maintainability, operability and throughput), and technology readiness

To structure this exploration, CEEC utilized the well known “Now–New–Next” framework, a conceptual tool to distinguish between:

- Now: technologies currently in commercial use and deployed at scale,
- New: emerging innovations with some level of piloting or early adoption, and
- Next: conceptual or early-stage developments that may define the future landscape.

This framework allowed workshop participants to anchor their evaluations across a temporal horizon, balancing operational realism with long-term vision. It also provided a common vocabulary for assessing maturity, risk, and innovation potential in a comparative and structured manner.

The following section describes the workshop's agenda and methodology in more detail, including how participants were grouped, the criteria used to assess the technologies, and the collaborative tools that enabled structured dialogue across disciplinary and organizational boundaries.

4. WORKSHOP STRUCTURE AND METHODOLOGY

The "Future of Comminution" workshop, hosted by CEEC on March 30, 2025, in Cape Town, was designed as an immersive, high-level technical forum. Its structure combined concise technical briefings, expert facilitation, and dynamic group discussions to foster deep and candid exchanges. Participants were drawn from across the mining value chain: senior leaders from mining companies, researchers, OEMs, technology developers, and process consultants. Importantly, all attended as individuals under Chatham House Rule, allowing for open expression without attribution.

Rather than presenting technologies in isolation, the workshop was structured around critical evaluation criteria. Participants were organized into seven multi-disciplinary groups, each assigned to evaluate a specific thematic dimension of technology performance—ranging from energy and emissions to maintainability and commercial readiness. This approach ensured that the evaluation was not driven by commercial interests or vendor advocacy, but by peer-to-peer technical scrutiny across relevant dimensions of operational performance and sustainability. Ultimately, the deeper purpose of the exercise was not just to enable a multi-dimensional assessment, but to strengthen the collective conversation, foster the exchange of perspectives, and reflect critically on the challenges of implementing new technologies in real mining environments.

The session opened with a brief overview of CEEC's mission and a framing presentation highlighting the challenges that comminution must overcome to support industry decarbonization and water goals. Prior to the workshop, each group received a curated set of one-page technology briefs (OnePagers) outlining a dozen emerging and established breakage technologies. A large-format visual worksheet was also provided to guide group discussions and capture inputs in a structured format. Finally, group outcomes were then presented in plenary, sparking broader reflections and shared learning.

5. WORKSHOP AGENDA

Session Title	Description
Welcome & Opening Remarks	Context from CEEC, framing the urgency of transformation in comminution.
Workshop Objectives & Instructions	Overview of methodology, tools, and expectations.
Technology Overview: "Now – New – Next"	Summary of 11 technologies and framework for assessment.
Group Work – Technology Evaluation (Part 1)	Evaluation using large-format worksheets and OnePagers.
Group Work – Technology Evaluation (Part 2)	Continuation of structured evaluation and prioritization.
Group Presentations (1–3)	First set of teams share outcomes and insights.
Group Presentations (4–7)	Remaining groups share evaluations.
Facilitated Discussion & Wrap-Up	Reflections, key themes, and proposals for future actions.

6. PARTICIPATING ORGANIZATIONS (NON-ATTRIBUTIVE)

The “Future of Comminution” workshop convened over 40 senior professionals representing a cross-section of the global minerals industry. Attendees were invited based on their technical expertise and leadership roles in areas such as comminution, process innovation, sustainability, and operations strategy.

In alignment with the Chatham House Rule, this report does not attribute individual comments or positions to specific participants or their affiliations. However, the following is a non-attributive summary of the types of organizations represented, illustrating the depth and breadth of engagement:

- **Mining Companies**
  - i. Major copper, gold, and battery mineral producers from North and South America, Africa, and Australia
  - ii. Mid-tier and emerging mining companies with a focus on innovation, brownfield and optimization.
- **Original Equipment Manufacturers (OEMs)**
  - i. Global OEMs specializing in comminution, dry grinding, and fine particle separation
  - ii. Suppliers with technologies in HPGR, vertical roller mills, and innovative crushing systems.
- **Research Institutions and Academia**
  - i. Universities with leading research programs in mineral processing, energy efficiency, and ore characterization
  - ii. Researchers involved in pilot programs and technology readiness assessments
- **Consulting and Engineering Firms**
  - i. Technical advisors with expertise in flowsheet design, techno-economic modeling, and mine-to-mill optimization
  - ii. Sustainability and ESG-focused consultants working on water, emissions, and tailings strategies
- **Industry Associations and NGOs**
  - i. Representatives from collaborative industry platforms promoting responsible and efficient resource development
  - ii. Experts affiliated with CEEC and its initiatives, including the CEEC Medals and Global Water Initiative

7. DESCRIPTION OF TECHNOLOGIES EVALUATED

RETHINKING BREAKAGE: NEW PRINCIPLES AND APPROACHES IN COMMINUTION

The set of technologies evaluated during the workshop represents a broad spectrum of physical breakage mechanisms and system-level innovations. Unlike conventional comminution circuits – largely dominated by impact and abrasion in wet environments using steel media – the innovations presented explore novel physical principles, targeted energy delivery, and alternative circuit architectures aimed at reducing energy and water use while improving liberation efficiency.

Several emerging technologies shift away from brute-force mechanical grinding toward selective breakage at the grain boundary, using tools like thermal stress, high-voltage electrical discharges, or transcritical fluid expansion. Others reimagine classical mechanics through new configurations that deliver impact, shear, or compression in more energy-efficient and potentially dry formats. Across the board, these technologies signal a move toward coarser liberation, dry processing, and integration with pre-concentration strategies – aligning closely with the industry's Net Zero, water reduction, and tailings minimization goals.

The following descriptions summarize each technology presented in the workshop.

HIGH-PRESSURE GRINDING ROLLS (HPGR)

HPGR is a well-established technology that uses interparticle compression in a packed bed between two counter-rotating rolls. By avoiding direct impact and leveraging compressive stress and applying energy directly to the bed of particles, the HPGR provides improved energy efficiency and reduced media consumption. It is widely applied in tertiary crushing and final grinding stages, and is increasingly integrated into flowsheets as a replacement or supplement to SAG mills.

VERTICAL ROLLER MILL (VRM)

VRM applies compression and shear forces through rollers operating on a rotating table. Originally developed for the cement industry, the VRM enables efficient fine grinding in a compact, dry-operable format. It has the potential to reduce water and energy demand while delivering a consistent particle size distribution.

COARSE STIRRED MILLING

This approach adapts the principle of stirred milling, traditionally used for fine and ultrafine grinding, to coarser size ranges. Coarse stirred mills aim to deliver efficient energy transfer with larger media than traditional applications.

CONJUGATE ANVIL HAMMER MILL (CAHM)

CAHM incorporates an outer ring, called the anvil, that rotates about a horizontal axis, while a second ring, called the hammer, is placed inside the anvil and rotates on a parallel, but offset, axis. Rocks are introduced into the gap above the hammer within the anvil. The system is designed to replace or complement SAG mills in primary grinding.

VERO LIBERATOR

The VeRo Liberator uses high-speed rotary elements to apply complex, multidirectional stresses (including shear and torsion) to ore particles. The design targets dry, selective liberation of minerals with minimal fines generation.

ELECTRICAL FRAGMENTATION

This technology applies high-voltage electrical pulses to induce dielectric breakdown within rock, resulting in internal fracturing along grain boundaries. Recent developments have demonstrated the feasibility of a continuous system, where rocks travel along a submerged screen that transmits the voltage pulse. While integration into full-scale processing circuits remains a challenge, the underlying principle offers a high-potential avenue for pre-weakening or selective breakage of ore.

MICROWAVE-ASSISTED COMMINUTION

Microwave energy is used to generate thermal stress within heterogeneous ore structures, creating internal microcracks that facilitate downstream breakage. This approach can be applied as a pre-treatment stage before conventional crushing or grinding. Pilot tests have demonstrated increases in throughput and reduced energy consumption, with potential benefits in ores that exhibit differential heating characteristics.

HIGH-PRESSURE SLURRY ABLATION (HPSA)

HPSA utilizes high-pressure fluid jets to generate surface erosion and particle disintegration via cavitation and turbulence. The technology employs a set of opposingly oriented nozzles to direct streams of high-pressure, high-velocity slurry into an impinging jet region where particle-particle collisions induce breakage. The slurry streams can collide either with each other (jet-to-jet) or against a surface (jet-to-plate), depending on the configuration.

MULTI-SHAFT MILL

The EDS Multishaft Mill is a compact vertical mill – utilising high-speed impacts to break down particles. The mill utilises a series of rotating horizontal shafts with flingers attached, which impact gravity fed material at very high speeds. The material is subjected to numerous impacts in an unpredictable and chaotic environment (milling chamber) before ejecting out the bottom of the mill (discharge section).

IMPTEC SUPER FINE CRUSHER

Developed to deliver very fine product sizes with minimal energy and media consumption, this crusher applies low-speed, high-pressure breakage through compression and interparticle forces.

TRANSCRITICAL CO_2 PULVERISATION

This highly novel concept involves saturating ore with CO_2 in its supercritical state and then rapidly depressurizing the system, causing explosive particle disintegration. The mechanism relies on a sudden phase change from supercritical to sub-critical leading to a pressure difference between the inside (pores/microfractures) and outside of a rock resulting into fracture.

8. WORKSHOP OUTCOMES: SUMMARY OF GROUP DISCUSSIONS

A. A SHIFT IN PERSPECTIVE: FROM EQUIPMENT TO SYSTEMS

Participants consistently emphasized the need to move beyond evaluating individual machines in isolation. Instead, many discussions gravitated toward understanding how each technology could integrate into a complete flowsheet, how it might impact liberation, classification, flotation, and tailings, and how it could reshape the energy–water–waste trade-offs of the overall system.

This systems-thinking approach was particularly evident in discussions around coarse particle liberation, dry circuits, and pre-conditioning technologies, where the impact of a new comminution method extended well beyond the grinding stage.

B. READINESS VERSUS POTENTIAL: A DELICATE BALANCE

Groups tasked with assessing Technology Readiness and Commercial Viability highlighted the wide disparity in maturity levels across the spectrum of emerging solutions. Some participants cautioned against overestimating early-stage technologies that currently lack robust pilot data or field validation. Others, however, emphasized that without active support for less proven but high-potential innovations, the sector may fall short in achieving its longer-term goals around emissions reduction, water use, and overall sustainability performance.

This tension between pragmatism and ambition shaped many of the workshop conversations, as participants grappled with how to weigh short-term trials against long-term transformative promise. The discussion underscored the difficulty of making fair comparisons when levels of information, testing environments, and commercial exposure vary so widely. It also revealed the importance of transparent, contextualized frameworks that allow emerging technologies to be assessed constructively—even when they are not yet fully proven.

C. ENVIRONMENTAL PERFORMANCE: TRADE-OFFS AND BLIND SPOTS

Environmental evaluation groups drew attention to trade-offs that are often overlooked in traditional techno-economic assessments. Several participants emphasized that certain emerging approaches—particularly those that eliminate or reduce the need for steel media—may represent significant advances in terms of emissions reduction and resource efficiency. Conversely, some solutions were flagged for their potential to increase secondary environmental burdens, such as higher water demand or the generation of ultra-fine tailings, which could complicate tailings management and water recovery efforts.

A recurring insight was that technologies enabling dry or coarse particle processing may deliver multiple environmental benefits, including reduced water consumption and simpler tailings handling. These features were seen as potentially synergistic with both decarbonization goals and broader circular economy principles. However, the groups also noted that environmental claims must be evaluated holistically, with attention to indirect impacts and implementation contexts that can significantly influence real-world outcomes..

D. MAINTAINABILITY, OPERABILITY AND RISK OF INTEGRATION

When viewed through the lens of maintainability and operability, participants highlighted a strong contrast between established technologies and newer, less familiar systems. Solutions grounded in conventional mechanical principles were generally seen as easier to integrate, with well-understood maintenance requirements and operator interfaces. In contrast, more novel configurations—especially those involving unfamiliar physical mechanisms or advanced control elements—were perceived as more complex and potentially disruptive to standard operational practices.

Common concerns included the availability of wear parts, system diagnostics, operator training needs, and the requirement for cross-disciplinary commissioning teams. These discussions reinforced the idea that technological innovation is not only a matter of performance or efficiency gains—it is also a matter of operational fit, cultural compatibility, and the practical realities of implementation in working mine sites.

E. ECONOMIC ASSESSMENT: RETHINKING COST DRIVERS

Economic evaluation groups urged a broader interpretation of CAPEX and OPEX. Several technologies appeared costly in isolation but offered potential downstream savings through reduced flotation residence time, lower energy in classification, or increased plant throughput. Others posed hidden costs related to infrastructure retrofits, space requirements, or regulatory compliance.

Importantly, many participants advocated for dynamic cost-benefit modeling that reflects the entire lifecycle value of new technologies, rather than upfront capital alone.

F. SHARED RECOMMENDATIONS AND EMERGING PRIORITIES

Across groups, several shared priorities emerged:

- The need to standardize technology evaluation frameworks across the industry, potentially building on CEEC's existing Energy Curves and extending them to water and emissions.
- The importance of supporting early-stage piloting and scale-up pathways, particularly for non-traditional technologies with high potential impact but low market traction.
- Recognition that flowsheet innovation – not just equipment substitution – will be critical to achieving system-wide improvements in energy, water, and waste.
- A call for greater visibility into performance under real operational constraints, including ore variability, maintenance cycles, and environmental compliance.

9. CROSS-CUTTING THEMES AND CONVERGING INSIGHTS

While each group in the workshop focused on a specific criterion, the true value of the exercise emerged in the overlaps and intersections between themes. Through plenary discussion and comparative review, several cross-cutting insights and converging messages came to light—highlighting where the industry's priorities align, and where further dialogue and investigation are needed.

A. SYSTEMS THINKING OVER SINGULAR PERFORMANCE

One of the clearest takeaways was the shift from evaluating technologies in isolation to assessing their flowsheet-level implications. Participants repeatedly emphasized that performance in one metric (e.g., energy or throughput) must be balanced against others, such as water demand, tailings behavior, or operability.

Technologies that demonstrated multi-dimensional benefits—even if moderate in each category—were often rated more favorably than those that excelled in one metric but performed poorly or remained unknown in others.

This systemic approach supports a broader industry shift toward holistic circuit design, where comminution is integrated with pre-concentration, coarse particle flotation, dry classification, and other water- and energy-efficient strategies.

B. MATURITY BIAS VS. INNOVATION OPPORTUNITY

The workshop surfaced a productive tension between technology readiness and transformational potential.

Participants generally favored established technologies (e.g., HPGR, VRM) for short- to medium-term implementation, but also recognized the need to proactively support and de-risk earlier-stage innovations. Without structured pathways for piloting, scale-up, and validation, breakthrough concepts may never leave the lab—even if they represent future standards.

There was broad support for developing a mining-specific TRL/CRI framework, with adjustments for context (ore type, site constraints, ESG priorities) to better reflect the realities of adoption risk in this sector.

C. OPERATIONAL FIT IS AS CRITICAL AS TECHNICAL MERIT

Across multiple groups, participants stressed that ease of operation, maintainability, and training requirements are often the decisive factors in technology selection—particularly in brownfield or remote sites with limited specialist support.

Technologies with complex infrastructure needs, unfamiliar control systems, or specialized safety protocols may face significant resistance, regardless of their technical advantages.

Conversely, innovations that are modular, intuitive, or designed for retrofitting were viewed as having greater chances of real-world success. The best technical solution means little if it cannot be trusted, understood, or serviced by site personnel.

D. BEYOND ENERGY: A BROADER DEFINITION OF EFFICIENCY

While energy consumption remains a primary performance metric, participants highlighted the growing importance of “compound efficiency”—technologies that simultaneously improve energy, water, tailings, emissions, and metallurgical outcomes.

For example:

- Coarse liberation supports both energy reduction and improved water recovery.
- Media-free grinding reduces both OPEX and Scope 3 emissions.
- Dry circuits offer pathways to eliminate both tailings ponds and reagent-intensive water treatment systems.

The convergence of these benefits underlines a new imperative: integrated efficiency, not just isolated optimization.

E. DATA GAPS AND THE NEED FOR STANDARDIZATION

Despite the technical strength of many proposals, participants noted recurring gaps in independent performance data, particularly around:

- Liberation profiles
- Water balance impacts
- Emissions per tonne of metal recovered
- Long-term maintenance and lifecycle cost data

These gaps complicate decision-making and delay the scaling of promising solutions.

F. STRATEGIC COLLABORATION FOR SHARED VALUE

Finally, the workshop reaffirmed the value of neutral, expert-driven spaces for shared technical exploration. Participants from competing companies, institutions, and geographies collaborated openly—demonstrating the potential for pre-competitive initiatives to accelerate change.

Multiple groups expressed interest in:

- Participating in joint piloting efforts
- Co-authoring technical assessments
- Contributing to the development of shared evaluation frameworks

The workshop itself was seen as a blueprint for future collaboration—proof that convening the right expertise, under the right rules of engagement, can unlock insight and trust across the industry.

10. CONCLUSIONS AND NEXT STEPS

SUMMARY OF KEY INSIGHTS

The “Future of Comminution” workshop brought together a diverse cohort of experts to tackle a deceptively simple question: what technologies will help mining break rock better, faster, cleaner, and smarter in the years ahead?

Through structured evaluation and candid discussion, several key conclusions emerged:

- **No single technology will solve the challenge alone**. Future gains in energy, water, and emissions efficiency will come from intelligently combining multiple innovations across the circuit.
- **Liberation efficiency is the new frontier**. Technologies that enable coarse, selective liberation—even at lower throughput—may deliver higher system-wide value than brute-force grinding at scale.
- **Maintainability and operability are gatekeepers to adoption**. No matter how efficient or innovative a technology may be, if it cannot be maintained, trusted, and operated by site personnel, it will not succeed in the field.
- **Dry and media-free systems represent a strategic shift**. These technologies not only reduce environmental impact and OPEX but unlock new flowsheet designs and eliminate infrastructure bottlenecks.
- **There is an urgent need for standardized, neutral benchmarking tools.** Frameworks for evaluating technologies across energy, water, emissions, cost, and liberation must evolve to reflect the complexity and interdependence of these variables.

STRATEGIC IMPLICATIONS FOR THE MINING INDUSTRY

The outcomes of this workshop suggest that rethinking comminution is not merely a technical upgrade-it is a strategic enabler for meeting Net Zero, ESG, and productivity goals. Companies that lead in adopting next-generation breakage systems will gain:

- Enhanced resilience in water- and energy-constrained environments
- Lower emissions across Scope 1, 2, and 3
- Better compatibility with dry stacking, coarse flotation, and early gangue rejection
- Faster path-to-permit and stronger social license through reduced environmental footprint
- Operational flexibility to respond to shifting ore types and regulatory conditions

However, to realize this potential, the industry must overcome persistent barriers: lack of pilot infrastructure, limited public data, and a cautious risk culture that favors the known over the new.

In addition to the high-level implications already addressed, the workshop surfaced several deeper strategic considerations that reflect the structural challenges facing the mining industry as it rethinks comminution. These reflections reinforce the need for system-wide innovation-not only in technology itself, but in the frameworks, assumptions, and investment models that surround it.

1. Beyond site-level trials: The need for coordinated validation frameworks

A recurring challenge in the technology development pathway is the industry's dependency on site-specific validation processes between mining operations and individual suppliers. While these relationships can yield valuable learnings, they are often constrained by local schedules, shifting operational priorities, and commercial asymmetry between operators and vendors. As a result, validation timelines become extended or inconclusive, and many promising technologies fail to reach maturity—not due to technical shortcomings, but due to fragmented validation pathways and lack of structured funding support.

To overcome this, there is growing need for a cross-industry, multi-site validation framework—one that offers standardization in testing protocols, structured data sharing, and support for ecosystem readiness. Such a framework would not only improve the quality and speed of validation outcomes but also lower the perceived risk for investors and end-users, offering greater predictability and de-risking for both capital deployment and technology uptake. It would allow technologies to mature in parallel across different ore types and contexts, improving both confidence and scalability.

2. More tools in the Toolbox: Moving beyond one-size-fits-all thinking

For decades, the industry has relied heavily on a narrow set of equipment types—SAG mills, ball mills, crushers, and more recently HPGR—as the default building blocks of comminution circuits. While effective in many contexts, this limited toolbox has led to a systemic tendency to retrofit ores to equipment, rather than selecting equipment based on mineral-specific behavior.

This generalized approach has created inefficiencies—particularly in deposits with complex mineralogy, high variability, or sustainability constraints. As the industry encounters more geologically diverse and environmentally sensitive projects, the limitations of "one-size-fits-all" become more apparent. Engineering teams designing new plants often face a constrained menu of options, making it difficult to build flowsheets that are truly optimized for their ore bodies.

Expanding the availability of modular, ore-specific, and well-validated technologies would allow engineers and operators to make more deliberate design decisions. Rather than betting on a single breakthrough, the industry must invest in a broader suite of proven options—a diversified, flexible toolbox that can be deployed strategically across ore types, regions, and project objectives.

3. Innovation must also focus on Existing Infrastructure

While emerging technologies offer exciting possibilities for the future, it is equally important to recognize the enduring presence of legacy comminution infrastructure. The majority of operating plants today—and many that will continue to operate into the next two to three decades—are built around SAB (SAG and Ball) configurations and conventional circuits.

This reality imposes a strategic imperative: we must improve what we already have, not just wait for what comes next. There are numerous underutilized opportunities for improving the energy efficiency, water performance, control systems, and metallurgical recovery of existing circuits. These may include optimization of classification systems, integration of sensors and advanced control, media and liner optimization, and process debottlenecking.

In many cases, incremental upgrades to existing circuits could deliver significant ESG and productivity gains at lower risk and lower cost than full-scale replacements. The industry must balance its forward-looking innovation efforts with a pragmatic focus on unlocking the latent potential of current assets.

4. Total ownership cost should Include Decarbonization Costs

A central barrier to the adoption of low-emission technologies lies in the mismatch between how costs are modeled and how value is created. Traditional project evaluation frameworks prioritize CAPEX and short-term OPEX, often excluding broader ESG costs and long-term liabilities.

To address this, the concept of Total Ownership Cost (TOC) should evolve to include the explicit cost of decarbonizing Scope 1, 2, and 3 emissions. This includes the cost of carbon credits or taxes, the investment required for electrification, the impact of grinding media production, and the lifecycle emissions of water and tailings treatment.

By embedding these factors into economic models, companies can make more accurate and holistic comparisons between flowsheet options. In many cases, technologies that appear costlier under traditional metrics may outperform when their full ESG-adjusted value is accounted for—

particularly as regulatory, investor, and social pressures make carbon accountability non-negotiable.

5. The hidden value of what a technology prevents

One of the most important shifts in thinking emerging from the workshop was a redefinition of how value is assessed. Traditionally, value is measured by what a technology delivers—more throughput, lower energy, higher recovery. However, in many cases, the true value lies in what it prevents.

This includes:

- Avoiding additional infrastructure investment (e.g., tailings thickening, water treatment)
- Reducing risk exposure (e.g., lower water withdrawal, less energy variability)
- Minimizing operational complexity or safety hazards
- Deferring the need for expansion CAPEX or environmental remediation

These avoided burdens—while harder to quantify—can materially shift the cost-benefit equation. A technology that reduces the need for high-pressure pumping or eliminates grinding media may not only cut costs but also simplify operations and reduce permitting complexity. Incorporating these considerations into technology evaluation frameworks is essential to support better long-term decision-making.

NEXT STEPS AND OPPORTUNITIES FOR CEEC

Building on the success of this workshop, CEEC and its network of advocates, sponsors, and collaborators are uniquely positioned to catalyze a new phase of structured, technically grounded innovation in comminution. Several priority initiatives were identified by participants as having the potential to accelerate this transformation:

Develop a Mining-Specific TRL/CRI Framework

There was unanimous agreement on the need to evolve beyond generic Technology Readiness Level (TRL) and Commercial Readiness Index (CRI) frameworks. The mining industry demands an evaluation model that goes beyond lab-scale validation and incorporates the realities of industrial deployment in complex, variable, and high-risk environments.

A Mining-Specific TRL should include not only traditional indicators of maturity, but also:

- Maintainability: Can the technology be serviced reliably in remote or resource-constrained operations?
- Operability: Is it compatible with existing workforce skills, safety protocols, and plant control systems?
- Integration Complexity: Can it be embedded into existing flowsheets without major redesigns?
- ESG Performance: Does it enable measurable progress in emissions, water use, tailings reduction, or safety?
- Flowsheet-Level Impact: Does it improve overall metallurgical performance, not just machine efficiency?

This expanded TRL would serve as a decision-making compass for operators, investors, and regulators, offering a nuanced view of a technology’s true readiness in the mining context.

11. FINAL NOTE & CALL TO ACTION

CEEC's value lies not in taking sides, but in bringing the right people to the table, asking the right questions, and framing them in a way that drives meaningful progress. This workshop was a step in that direction—and the insights it generated offer a powerful foundation for action.

One point emerged with absolute clarity: **rethinking comminution is not just a technical challenge—it is a strategic necessity**. The path to a lower-carbon, water-efficient, and economically resilient mining future runs directly through how we break rock. But that path must be built much faster than current industry timelines suggest.

Neither the mining industry nor society at large can afford to wait another 20 or 30 years for new technologies to be ready at scale. The urgency of the ESG agenda demands agility. Without it, we risk being trapped in a worsening paradox: a world that requires exponentially more metals for the energy transition, but where the methods we use to produce those metals no longer meet environmental or social expectations.

This is not a distant risk—it is a present constraint. The pressure between surging demand for metals and tightening ESG regulations will only intensify. In this context, investing in the acceleration and adoption of innovative comminution technologies is not only the right thing to do—it is also the most economical and least disruptive path forward.

In the end, the cost of not advancing will be higher than the cost of investing early. It is more affordable—and more responsible—to evolve our processes in harmony with society and the environment than to operate under constant threat of social, regulatory, and reputational conflict.

The future of comminution is not written yet. But thanks to the insight and urgency demonstrated by this community, it is beginning to take shape—with clarity, direction, and purpose.

12. ACKNOWLEDGEMENTS

CEEC extends its deepest thanks to all those who made the **"Future of Comminution" Workshop** possible—not only as a singular event, but as part of an ongoing, collaborative effort to accelerate innovation and sustainability in mineral processing.

We are especially grateful to **our sponsors**, whose commitment and vision continue to fuel CEEC's mission of advancing energy-efficient and low-impact comminution solutions across the mining sector. Their ongoing support enables us to maintain independence, uphold technical rigor, and bring together diverse voices from across the industry.

Our sincere appreciation also goes to the **participants of the workshop**, whose openness, expertise, and willingness to engage in honest, technically grounded dialogue formed the heart of this initiative. Their contributions—spanning operating companies, OEMs, research institutions, and consultancies—reflect the broad base of talent and commitment needed to tackle the complex challenges facing our industry.

We also acknowledge with gratitude the team at **MEI (Minerals Engineering International)**, organizers of the Comminution '25 conference, for their generous collaboration and logistical support. Their partnership was essential to the success of this workshop, and their longstanding role in fostering global exchange around comminution has helped shape the collective understanding upon which this initiative was built.

Together—with our sponsors, collaborators, and technical community—we reaffirm CEEC's mission to act as a neutral, evidence-based platform for identifying, promoting, and accelerating the solutions that will define the future of comminution.

APPENDIX – THEMATIC INSIGHTS FROM THE MULTICRITERIA ANALYSIS

1. THEME: TECHNOLOGY AND COMMERCIAL READINESS

The group tasked with evaluating Technology and Commercial Readiness was responsible for assessing the maturity and implementation potential of each technology. Their discussion considered not only traditional Technology Readiness Levels (TRLs), but also the more nuanced Commercial Readiness Index (CRI), recognizing that a technology's pathway to impact depends as much on commercial scale-up as on technical viability.

The evaluation focused on factors such as:

- Validation through industrial or pilot-scale testing
- Proven ability to integrate into an operating plant
- Reliability of supporting data and peer-reviewed evidence
- Manufacturing and supply chain availability
- Perception of risk by operators and investors

This group made a clear distinction between technologies with demonstrated commercial use, emerging technologies with early-stage pilots, and those still in conceptual or lab-scale development. Their findings are summarized below.

A. TECHNOLOGIES WITH PROVEN COMMERCIAL USE

This category encompasses technologies that have a demonstrable track record in industrial operations. These solutions benefit from extensive performance data, established supplier ecosystems, and well-defined integration pathways. In general, they are perceived as low-risk options with high operational certainty, particularly for sites aiming to optimize within known parameters.

Participants noted that technologies in this group often serve as a benchmark against which newer concepts are measured. However, they also highlighted that even proven technologies may face inertia in certain contexts due to cultural, contractual, or infrastructure-related factors.

B. TECHNOLOGIES WITH EMERGING INDUSTRIAL PILOTS

Technologies in this group have moved beyond laboratory validation and are undergoing initial piloting in industrial contexts. While they show promise across one or more dimensions—such as energy efficiency, selective breakage, or footprint reduction—they are still navigating the uncertainties of scale-up and integration.

Participants emphasized that piloting environments are critical enablers of progress for this cohort. In many cases, technologies in this group were seen as conceptually sound, but still in need of independent performance validation, stronger operational data, and clearer cost-benefit cases. Willing operator partnerships and shared piloting infrastructure were highlighted as key accelerators for this stage of development.

C. CONCEPTUAL AND EARLY-STAGE INNOVATIONS

A third category discussed by the group comprised technologies still in early-stage or conceptual development, with limited evidence of industrial validation or structured scale-up planning. These innovations often introduced novel physical principles or configurations that diverge significantly from established processing paradigms.

While participants acknowledged the creative potential of these concepts, they also noted that such technologies tend to face high uncertainty across multiple dimensions: operability, safety, energy balance, cost of deployment, and compatibility with existing plant infrastructure. In many cases, the absence of peer-reviewed data, engineering design packages, or transparent technical documentation made it difficult to assess their real-world feasibility.

Some concepts prompted interest due to their potential for step-change improvements in breakage efficiency, media reduction, or circuit simplification. However, skepticism arose when performance claims were not substantiated by independently verified results or when foundational engineering assumptions remained unclear.

The group agreed that these lower-readiness innovations should not be dismissed out of hand. Rather, they require a careful approach—one that supports rigorous technical vetting, early-stage collaboration with research institutions and operators, and the development of realistic demonstration pathways. Advancing from concept to commercial relevance will depend on building credibility, improving data transparency, and fostering environments that allow high-risk, high-reward technologies to be safely and objectively tested.

Importantly, many of these early-stage technologies are attempting to solve limitations that current mainstream solutions do not adequately address. This makes it all the more critical for the industry to take a proactive stance—observing these innovations closely, creating structured pathways for piloting, and offering them the opportunity to succeed or fail through real-world application. A thriving innovation ecosystem must include space for exploration, iteration, and learning—even where the outcomes are uncertain.

D. ADDITIONAL CONSIDERATIONS AND REFLECTIONS

Beyond the classification of technologies by their level of readiness, the group's discussions surfaced a series of systemic and cross-cutting insights that have significant implications for how innovation is evaluated, de-risked, and supported within the mining sector. These reflections provide valuable context for interpreting readiness and highlight structural challenges that must be addressed to accelerate the responsible adoption of new technologies

- **Readiness is Ore and Site-specific:** One of the clearest conclusions was that technological maturity cannot be assessed in isolation. The same solution may perform exceptionally in one geological setting but fail in another due to differences in mineralogy, ore hardness, clay content, moisture, and throughput expectations. This makes blanket TRL or CRI ratings inherently problematic unless they are contextualized through defined operational archetypes or application profiles. A technology deemed "ready" in one context may require significant adaptation to be viable elsewhere.
- **Perception and trust matter**: Even when a technology is technically sound, a lack of accessible, third-party validated data can delay or derail adoption. Participants emphasized that investor and operator confidence is built through transparency-clear performance benchmarks, credible pilot results, and a willingness to share both successes and limitations. Technologies that withhold critical information or rely solely on vendor-supplied data are often viewed with skepticism, particularly in capital-intensive sectors such as mining where the cost of failure is high.

  For technology developers who consider their systems perform better than reflected during the workshop, this presents a valuable opportunity—not a threat. The workshop's findings highlight the importance of proactive disclosure. Sharing robust, verifiable technical information through peer-reviewed papers, technical

sessions, and public case studies can significantly enhance market understanding and confidence. Rather than dismissing critical feedback, companies may choose to view it as a prompt to strengthen their visibility and credibility across the broader ecosystem.

- **Piloting infrastructure is a bottleneck**: Many promising ideas remain stuck in the lab due to the high cost, complexity, and operational risk of pilot-scale trials in mine sites. Participants agreed that while early-stage technologies may demonstrate significant theoretical or lab-scale advantages, their progress stalls without access to real operational environments. The absence of standardized piloting frameworks, funding mechanisms, and neutral testbeds significantly limits the ability to validate performance under representative conditions.

  This challenge also underscores a collective industry responsibility. Operators, OEMs, and research institutions could benefit from exploring shared piloting models—whether through regional hubs, multi-party consortia, or pre-competitive collaborations—to lower the barrier to entry for field validation. For developers, the takeaway is clear: planning for piloting from the outset, including partnerships, engineering readiness, and data capture strategies, can dramatically improve the chances of successful scale-up and industry recognition.

- **Readiness is not binary**: A technology may be "ready" in principle—demonstrating acceptable performance in controlled conditions or simulations—but still struggle to gain traction due to the absence of surrounding ecosystem enablers. These include supplier networks, after-sales service, spare parts logistics, operator training programs, regulatory alignment, and engineering integration pathways. Without these foundational supports, even technically mature solutions can face long deployment timelines, increased operational risk, and resistance from end users.

  For technology developers, this highlights the importance of viewing readiness as a systemic property, not just a technical milestone. Ecosystem readiness must be intentionally cultivated alongside R&D. Mapping out serviceability, integration tools, and training strategies early in the development process can help avoid late-stage barriers. **The earlier that maintainability, serviceability, interoperability, and workforce competency matrices are incorporated into the design phase, the greater the likelihood of successful adoption and sustained performance in real-world operations.** For mining companies and investors, incorporating ecosystem readiness into technology assessments may offer a more realistic measure of deployment feasibility and long-term reliability.

2. THEME: ENERGY EFFICIENCY

The group assigned to assess energy efficiency and consumption focused on one of the most critical drivers of innovation in comminution, the sector's disproportionately high energy demand. As mining pushes into lower-grade ores and deeper deposits, reducing the energy intensity of breakage is no longer a marginal gain—it is a strategic necessity.

Discussions in this group were grounded in both comparative performance metrics (energy per tonne) and in the quality of energy use—that is, how precisely energy is applied to achieve effective breakage and mineral liberation. Participants also considered how energy performance might vary under different ore conditions, circuit configurations, and operating scales.

A. TOP PERFORMERS IN ENERGY EFFICIENCY

The group identified several technology approaches that exhibit strong alignment with the principles of energy-efficient comminution. These solutions, though varied in design, share a number of important operational traits: the ability to apply energy through targeted, high-pressure mechanisms; minimal reliance on grinding media; and compatibility with dry processing environments.

Participants emphasized that technologies designed to maximize interparticle breakage—particularly those that concentrate energy where fractures are most effective—tend to outperform more diffuse or impact-heavy methods in terms of energy input per tonne. Compression-based mechanisms, when engineered to match ore-specific fracture patterns, were seen as especially efficient.

Another recurring feature of top-performing approaches was the potential for integration into dry or hybrid flowsheets, especially in arid regions or jurisdictions with high energy tariffs. Dry processing not only lowers water dependency but also improves energy transfer efficiency by reducing losses associated with slurry handling, pumping, and dewatering.

Beyond machine design, participants also underscored the importance of operational maturity and learnings from deployment at scale. Technologies that have been implemented across multiple sites—particularly where they've been optimized for different ore types and plant configurations—were perceived as offering greater certainty and lower implementation risk, in addition to their energy benefits.

B. ENERGY EFFICIENCY IN EMERGING AND EXPERIMENTAL TECHNOLOGIES

The group also examined a range of emerging and early-stage technologies that propose novel pathways to reduce energy consumption in comminution. While these approaches often introduced unconventional mechanisms—ranging from thermal pre-conditioning to novel mechanical configurations—they shared a common challenge: limited data under industrial conditions.

Participants noted that many of these solutions demonstrate theoretical energy advantages or promising laboratory-scale results, particularly in terms of improving liberation with less mechanical input or by minimizing unnecessary fine grinding. Some were seen as potentially transformative in how energy is delivered—focusing it more selectively at grain boundaries or structurally weaker zones in the ore.

However, several members of the group emphasized the importance of validating these claims through real-world pilot testing, where throughput rates, energy balances, and integration complexity can be more accurately measured. In some cases, technologies that appear efficient on paper may encounter scale-up challenges related to auxiliary energy consumption, control systems, or material handling constraints if not addressed properly at early stages.

A particularly interesting insight was the shift in how energy efficiency is being defined. Instead of focusing solely on **energy per tonne processed**, several participants advocated for metrics like **energy per tonne of recovered metal or per tonne of liberated valuable mineral**. These perspectives highlight that energy savings must be considered in the context of downstream impacts, not just immediate breakage mechanics.

The attendees also discussed the strategic role of coarse grinding innovations, which aim to avoid unnecessary reduction of particle size before flotation. These solutions, if effectively paired with coarse particle flotation or other selective separation techniques, may allow for re-engineered flowsheets that consume significantly less energy overall—even if the energy demand of the breakage device itself is not radically lower.

C. ENERGY-INTENSIVE OR UNCLEAR CONCEPTS

The group identified a subset of technologies whose energy profiles remain difficult to quantify or raised concerns due to the apparent intensity of their underlying processes. These evaluations were conducted based on the information and technical knowledge available to participants at the time of the workshop. While conceptually innovative, many of these technologies involve complex physical mechanisms or thermodynamic cycles that are not yet well-characterized through empirical data or peer-reviewed studies.

Several of these approaches appear to require significant auxiliary energy inputs—such as for fluid pressurization, gas compression, or pulsed energy systems—which may offset potential gains in selective breakage or circuit simplification. Without comprehensive system-level energy balances, participants noted it is challenging to determine whether the net energy performance is competitive compared to conventional methods.

Another recurring concern was the lack of validated field data. For technologies still in conceptual stages or with proprietary components, the absence of transparent reporting on energy consumption per tonne, throughput capacity, or efficiency under load conditions left many participants hesitant to make firm assessments. In such cases, perceived uncertainty itself became a barrier to favorable evaluation.

Participants also emphasized that thermodynamic and mechanical complexity can compound risk—especially in energy-constrained or cost-sensitive environments. Technologies that introduce novel energy cycles or unfamiliar operational principles may require not only higher capital and operating inputs, but also bespoke training, monitoring, and support infrastructure, further complicating adoption.

However, the group was careful not to dismiss these innovations outright. Several participants argued that high theoretical energy use does not automatically disqualify a technology, particularly if it enables broader system-level benefits such as reduced water use, tailings simplification, or novel product streams. The key, they concluded, is transparent quantification and real-world validation under diverse site conditions.

D. KEY OBSERVATIONS AND RECOMMENDATIONS

The group's reflections went beyond device-level evaluations and emphasized the need to reframe how **energy performance is assessed and optimized across the comminution system**. Four key insights emerged from their discussions:

- **Energy metrics must reflect value delivered, not just tonnes processed**. Participants agreed that evaluating technologies based solely on energy per tonne processed may miss the broader picture. More insightful benchmarks might include energy per tonne of recovered metal or per tonne of liberated valuable mineral—especially for systems designed to enable coarse particle flotation or early gangue rejection.

- **Removing grinding media offers systemic benefits**. Solutions that eliminate or minimize the use of steel media were considered particularly attractive mainly due to reductions in Scope 3 CO_2 emissions.
- **Integration defines true energy performance**. Technologies that appear modest in standalone efficiency may unlock significant value when deployed in reengineered flowsheets—such as those featuring dry classification, ore sorting, or coarse flotation. Participants emphasized that energy savings must be evaluated across the circuit, not just at the point of breakage.
- **Benchmarking remains essential—but must evolve**. There was consensus that tools like CEEC's Energy Curves are vital for transparent comparison, but many noted that such tools need to adapt to accommodate emerging technologies that fall outside traditional SAG-ball paradigms. Flexible, standardized benchmarking frameworks could help validate novel approaches and facilitate broader industry acceptance.

In summary, the group underscored that achieving step-change reductions in energy use will require a dual focus: innovations in machine design and innovations in system integration. Technologies that deliver targeted breakage, avoid unnecessary fine grinding, and align with new separation strategies are likely to play a central role in the next generation of low-energy comminution systems.

3. THEME: WATER USE AND TAILINGS IMPLICATIONS

Water is rapidly emerging as one of the most critical and contentious resources in mining operations worldwide. From regulatory pressure and community expectations to operational constraints and climate variability, water availability and quality now define the viability of both existing mines and future projects. In this context, comminution technologies that minimize water usage—or reduce the generation of fine tailings that complicate water recovery—are gaining significant strategic relevance.

The group assigned to assess water use and tailings implications was tasked with examining how each technology affects the volume and quality of water required in the circuit, and how it influences the nature and manageability of tailings.

A. DRY PROCESSING AND WATER INDEPENDENCE

One of the clearest opportunities identified by the group lies in the development and implementation of dry or near-dry comminution flowsheets. Technologies capable of operating without the need for process water in grinding—especially when integrated with dry classification or air-based separation—could significantly reduce the overall water footprint of mining operations.

Dry grinding solutions offer several strategic benefits. First, they reduce or eliminate the need for slurry transport systems such as hydrocyclones, pumps, and associated piping, which not only consume water but also energy. Second, by avoiding slurry formation, these technologies simplify tailings handling and open pathways to dry stacking or filtered tailings strategies, which are increasingly favored by regulators and communities.

However, participants highlighted that the success of dry comminution is contingent upon a systems-level approach. That is, it is insufficient to focus solely on the grinding stage. Downstream elements—such as classification, beneficiation, and tailings deposition—must also be compatible with reduced water regimes. In many operations, this will require substantial reengineering of the process plant, as well as new design philosophies around tailings, dust control, and material handling.

The group also noted that while dry technologies are often associated with arid environments, they could bring value in temperate zones as well by reducing environmental liabilities, permitting hurdles, and water-related operational risks.

B. FINE TAILINGS AND DEWATERING CHALLENGES

A major concern raised in the workshop was the proliferation of ultra-fine particles resulting from certain breakage mechanisms. Technologies that apply high-intensity energy or rely on erosive or impact-based methods often produce particle streams that are difficult to dewater and manage.

These ultra-fines complicate thickening and filtration, increase the requirement for flocculants, extend dewatering times, and result in tailings that retain more water—posing challenges for transport, storage, and long-term closure. Participants expressed concern that even technologies with attractive energy profiles may introduce downstream water penalties if they generate excessive slimes.

In contrast, comminution strategies that favor coarser breakage—without sacrificing liberation—can improve tailings characteristics significantly. Coarser tailings are easier to dewater, more stable when stacked, and more amenable to emerging technologies like coarse particle flotation or dry stacking. Such approaches not only reduce water retention but also improve operational flexibility and alignment with closure objectives.

The group emphasized the importance of evaluating tailings characteristics early in the technology development process. A technology that excels in energy or throughput metrics but creates complex or unstable tailings may encounter resistance from operators, regulators, and communities alike.

C. TECHNOLOGIES PROMOTING COARSE LIBERATION

Closely linked to the discussion on tailings was the theme of coarse liberation. Participants showed strong interest in approaches that enable effective liberation of valuable minerals at larger particle sizes. These technologies hold the potential to reduce unnecessary fine grinding, which has cascading benefits for water, energy, and tailings.

Coarse liberation is especially relevant in the context of water stewardship. By avoiding the creation of fines and slimes, these approaches reduce the surface area of tailings particles, enhance drainage characteristics, and improve the performance of dewatering equipment. In many cases, coarser tailings are also more compatible with reuse scenarios or innovative disposal methods.

Workshop discussions also highlighted that coarse liberation strategies often rely on upstream enhancements—such as selective weakening or precision breakage techniques—that increase the probability of liberating minerals without full particle size reduction. This shift in design philosophy, from indiscriminate size reduction to targeted liberation, could reshape how future comminution circuits are conceived.

D. INTEGRATION WITH WATER-EFFICIENT FLOWSHEETS

The group was emphatic that water use cannot be evaluated in isolation at the equipment level. Water performance is a property of the entire flowsheet, and its optimization depends on the coordinated interaction of breakage, classification, separation, and tailings management.

Several integration strategies were discussed, including:

- The use of coarse liberation to enable early-stage gangue rejection, thereby reducing the mass and volume of material requiring downstream processing.
- Alignment of breakage technologies with dry or filtered tailings strategies, allowing for the complete removal of tailings dams in some scenarios.
- Incorporation of water balance modeling and simulation tools to quantify the system-wide impact of adopting new technologies and to identify hidden trade-offs.

Participants noted that many of the barriers to water-efficient processing are not technological but systemic—linked to legacy infrastructure, outdated permitting frameworks, or siloed engineering practices. Overcoming these requires a shift in mindset: from optimizing individual unit operations to redesigning entire value chains around water as a finite, high-value input.

The group stressed that water performance must be considered at the flowsheet level, not just at the equipment level. Several technologies were discussed in terms of how they might enable or complement broader water-saving strategies:

- Coarse liberation technologies can support early gangue rejection, reducing the volume of material that needs to be processed downstream—and therefore the overall water requirement.
- Dry or near-dry technologies were seen as more compatible with dry stacking or filtered tailings, which are increasingly preferred from a permitting and closure standpoint.
- Some participants emphasized the importance of integrating real-time water balance modeling into technology evaluation, to ensure that water benefits are quantified and verified across the system.

E. KEY TAKEAWAYS AND RECOMMENDATIONS

The group's reflections led to a clear consensus: water must no longer be treated as a secondary or passive constraint in comminution design—it should be a proactive, central criterion in the evaluation, development, and deployment of new technologies. This paradigm shift is critical to ensuring that innovation in breakage technologies aligns with the mounting pressures on water availability, regulatory compliance, and social license to operate.

Importantly, this also underscores the need to embed water planning as a core element of mine project engineering—not only from a hydrological or hydrogeological perspective, but as a fundamental input to metallurgical processing. Water availability and quality must be considered alongside energy, ore characteristics, and infrastructure in shaping a project's design basis and permitting strategy. As such, water becomes one of the critical resources that define the Life of Mine (LoM), influencing long-term production plans, processing flowsheets, technology selection, and closure approaches.

Some key takeaways included:

- Technologies that generate coarse, well-draining tailings are increasingly valuable—even if their energy performance is only modest.
- Fully dry circuits, though challenging to implement, may offer the best long-term resilience in water-scarce regions.
- The industry's current water evaluation frameworks are not well-suited to emerging technologies; new tools are needed to assess the interplay between breakage, particle size distribution, and water behavior.
- CEEC was encouraged to explore the development of Water Curves, analogous to the Energy Curves initiative, to benchmark and visualize water impacts across different comminution strategies.

Overall, the water and tailings group brought forward a powerful insight: in the next decade, the technologies that succeed will not only break rock better—**they will leave it drier, cleaner, and easier to manage**.

4. THEME: ENVIRONMENTAL EMISSIONS

As the mining sector comes under growing pressure to reduce its environmental footprint, emissions intensity—including greenhouse gas emissions, particulate release, and embedded carbon in inputs like grinding media—has become a critical dimension for evaluating comminution technologies. The group responsible for this theme focused on both direct emissions (e.g., energy source, media wear) and indirect or embodied emissions, considering the full life cycle of the technologies involved.

Their analysis underscored a fundamental shift: energy efficiency alone is no longer enough. The emissions profile of a comminution technology must now be viewed through the broader lens of supply chain carbon, waste streams, and the potential to reduce or eliminate carbon-intensive process inputs.

A. ELIMINATING GRINDING MEDIA: A DIRECT PATH TO EMISSIONS REDUCTION

A key opportunity identified by the group lies in the elimination or minimization of grinding media. Steel media represents a substantial source of Scope 3 emissions due to its manufacturing footprint, transportation, and ongoing replacement. Technologies that enable media-free or media-light operations offer a direct route to emissions reductions—both by removing this carbon-intensive input and by simplifying downstream logistics and procurement.

The group noted that even where electricity is sourced from low-carbon grids, the cumulative emissions associated with grinding media can remain significant. By focusing on alternative breakage mechanisms—such as targeted energy application, mechanical compression, or pre-conditioning—new systems can dramatically reduce the lifecycle carbon burden of comminution circuits.

B. EMISSIONS FROM ENERGY CONSUMPTION: THE ROLE OF SOURCE AND INTENSITY

The emissions intensity of a comminution technology depends not only on how much energy it consumes, but on the carbon profile of the energy source. For example, technologies operating in regions with predominantly hydro, solar, or wind energy will exhibit a far lower emissions footprint than those connected to coal- or diesel-dominated grids.

Participants emphasized that emissions per tonne of ore are a useful metric, but emissions per tonne of recovered metal—or per tonne of liberated valuable mineral—may offer a more accurate representation of a technology's sustainability performance.

This underscores the need for site-specific assessments, where power sourcing, circuit configuration, and ore characteristics are considered jointly. Additionally, there was strong support for encouraging technology developers to present emissions performance scenarios under different grid compositions.

The group stressed the importance of evaluating emissions per tonne of recovered metal, not just energy use per tonne of ore—a more meaningful metric in the context of sustainability goals.

C. PROCESS EMISSIONS AND FUGITIVE IMPACTS

Workshop participants also explored indirect emissions and environmental consequences, such as fugitive dust, reagent consumption, and tailings behavior. These impacts, while not always reflected in standard emissions accounting, can contribute significantly to a site's environmental footprint.

Technologies enabling dry comminution were seen as potentially advantageous in minimizing off-gassing, slurry aerosol, and chemical runoff associated with wet processing. However, this advantage comes with the need for effective dust containment and worker exposure management.

Conversely, certain wet processes—particularly those generating ultra-fine particles—were flagged for increasing downstream emissions via water treatment requirements, increased flocculant use, and emissions from tailings storage.

The group agreed that environmental performance must account for these operational externalities, which often emerge only when technologies are viewed in the context of the broader process and site layout.

D. SUPPLY CHAIN AND LIFECYCLE CONSIDERATIONS

A forward-looking point raised by the group was the need to evaluate emissions not just during operation, but across the technology lifecycle.

- How carbon-intensive are the materials used to build the equipment?
- What is the expected lifetime of wear parts, and how often must they be replaced?
- Can the technology be recycled, repurposed, or reconditioned at end-of-life?

In this regard, modular, low-maintenance systems—especially those designed for low-wear operation or simplified construction—were viewed as more aligned with long-term sustainability expectations.

E. CONCLUSIONS AND STRATEGIC IMPLICATIONS

This group's work reinforced the idea that environmental emissions are a systems property, not an equipment attribute alone. Technologies that reduce emissions tend to share three traits:

1. They eliminate or reduce grinding media.
2. They enable coarse liberation, minimizing overgrinding and waste.
3. They are compatible with low-carbon power sources and dry tailings strategies.

Participants strongly recommended that emissions benchmarking be integrated into CEEC's broader evaluation frameworks—potentially in partnership with life cycle assessment (LCA) experts or ESG-focused research institutions.

In summary, the shift toward Net Zero will not be driven by marginal gains in kWh/t, but by fundamentally rethinking the emissions architecture of mineral processing; in that vision, comminution technologies play a pivotal role.

5. THEME: COST STRUCTURE CAPEX AND OPEX

While comminution has long been recognized as the largest consumer of energy in mineral processing, it is also one of the largest cost centers, both in terms of capital expenditures (CAPEX) and ongoing operating expenses (OPEX). The group assigned to assess cost structure approached the topic holistically, evaluating not just upfront equipment costs, but also the broader financial implications of each technology: maintenance, media consumption, infrastructure requirements, and indirect impacts on throughput and recovery.

Participants emphasized that low cost is not always synonymous with high value, and that future comminution strategies must weigh cost against performance, sustainability, and flexibility in a rapidly evolving operational context.

A. CONVENTIONAL TECHNOLOGIES AND FAMILIAR COST PROFILES

Established comminution technologies are often well understood in terms of cost structure. Their financial performance is backed by extensive operational data, and their supply chains, maintenance regimes, and consumables markets are mature. These systems were seen as "known quantities"—not necessarily the cheapest options, but predictable in budgetary planning and often financeable via conventional means.

From an OPEX standpoint, systems that reduce grinding media consumption and exhibit lower maintenance intensity are generally favored. However, high initial CAPEX—particularly related to structural supports, dust control, and integration with surrounding infrastructure—remains a limiting factor for some operations. That said, in dry regions or areas with expensive water management requirements, certain conventional systems may offer hidden cost advantages by minimizing reliance on water-based processing.

B. EMERGING TECHNOLOGIES WITH DISRUPTIVE COST PROFILES

Several newer technologies were viewed as having the potential to reshape cost structures—not necessarily because of lower equipment prices, but due to their broader implications across the processing chain. These solutions may enable coarser grinding, reduce slurry transport, or accelerate downstream separation processes, all of which can shift the economic equation in meaningful ways.

In some cases, technologies with higher CAPEX may yield lower OPEX through reductions in media use, energy consumption, or wear part replacement. Others may simplify flowsheets, removing the need for large-scale tailings infrastructure, flotation units, or thickening circuits. Participants noted that the total cost of ownership (TCO) for these solutions depends heavily on site-specific variables, including ore characteristics, existing plant configuration, and regional infrastructure costs.

C. HIGH UNCERTAINTY AND RISK-ADJUSTED COSTS

A subset of technologies was classified as high uncertainty, where either the CAPEX or OPEX remains poorly characterized. For these systems, cost projections are still largely speculative, and depend on assumptions around scale-up, deployment, and operational performance.

Participants emphasized the need for robust sensitivity analysis and scenario modeling when evaluating these options. Questions around auxiliary infrastructure—such as thermal management, fluid systems, or specialized electrical installations—add complexity to the cost case. Similarly, the lack of publicly available performance data or implementation references hinders financial confidence.

As such, these technologies may require collaborative piloting, early adopter partnerships, and tailored financing mechanisms to advance toward commercial readiness.

D. COST AVOIDANCE AS STRATEGIC VALUE

An important insight from the group was the value of cost avoidance—the savings achieved not through lower purchase prices, but by eliminating expensive ancillary systems or operational steps. Technologies that reduce fines generation, for example, may avoid the need for high-capacity paste thickeners, flocculants, or dewatering plants. Dry or low-water systems may eliminate the capital and operating burden of water treatment, pumping, or desalination infrastructure.

Additionally, reducing reliance on grinding media not only lowers material costs, but also simplifies logistics, and decouples operations from volatile steel markets. Participants emphasized that these indirect benefits often go unrecognized in standard CAPEX/OPEX evaluations, and should be explicitly included in economic comparisons moving forward:

- Technologies that reduce fines generation may eliminate the need for complex thickening or paste tailings plants.
- Dry technologies may bypass water treatment, desalination, or pumping infrastructure—capital elements that can dominate budgets in remote or arid locations.
- Lower media use not only reduces OPEX, but simplifies logistics, safety management, and procurement dependencies.

This concept of cost avoidance is especially relevant in the current landscape, where capital is limited, and ESG risks can translate into financial penalties or permitting delays.

E. FINANCIAL FLEXIBILITY AND RISK MANAGEMENT

Participants discussed the implications of technology selection for financial flexibility and risk management. Solutions with modular footprints, scalable configurations, or low civil requirements were viewed positively—especially for brownfield projects, space-constrained sites, or regions with limited permitting capacity.

Conversely, technologies that require bespoke infrastructure, specialized commissioning, or high engineering effort were seen as financially riskier, even if they offer long-term performance benefits. The ability to stage investments, defer non-critical elements, or integrate gradually was seen as a key enabler of adoption.

There was broad agreement that standardized financial modeling tools, including lifecycle-based TCO frameworks and ESG-integrated investment templates, would significantly enhance the industry's ability to evaluate high-potential but complex technologies.The group also reflected on the financial implications of innovation:

- Technologies with modular footprints, low civil requirements, or scalable deployment were viewed favorably from a risk management perspective, especially in brownfield environments or constrained sites.
- On the other hand, some of the more complex or unproven technologies may require custom infrastructure, higher upfront engineering effort, and bespoke commissioning, which could deter investment even if long-term benefits exist.

F. KEY TAKEAWAYS

- CAPEX/OPEX trade-offs must be considered over the full flowsheet lifecycle. Technologies that appear expensive at the equipment level may deliver significant downstream savings.
- Media reduction remains one of the clearest pathways to reducing both OPEX and Scope 3 emissions.
- Cost neutrality alone is insufficient—stakeholders value solutions that simplify operations, reduce risk, or accelerate return on investment.
- Transparent piloting, reliable reference data, and clear implementation pathways are essential to unlock commercial financing for innovative but unproven technologies.

In conclusion, the group recognized that in a capital-constrained, ESG-driven industry, the comminution technologies that succeed will not necessarily be the cheapest—but they will be the ones that change the cost structure of mining itself.

6. THEME: MAINTAINABILITY AND OPERABILITY

While innovation in comminution often focuses on energy and throughput, no technology can succeed at scale if it cannot be maintained and operated reliably. This group examined each technology through the lens of operational practicality: How easy is it to maintain? How intuitive is its interface? Does it fit into the daily reality of a plant or require radical changes in workflows, skills, and safety protocols?

Their discussion emphasized that adoption risk is not only technical or financial—it is cultural and organizational, particularly in brownfield sites with established operational norms.

A. TECHNOLOGIES WITH OPERATIONAL FAMILIARITY

Technologies that build on existing operating principles—HPGR, VRM, and to some extent fine grinding mills—were seen as favorable from a maintainability and operability standpoint.

B. TECHNOLOGIES RAISING OPERATIONAL COMPLEXITY

In contrast, several emerging technologies were identified as posing operability challenges due to unfamiliar operating principles, control systems, or safety requirements. Even when mechanical complexity is reduced, novel inputs (e.g., high voltage, electromagnetic energy, gas pressure systems) often require new competencies or protocols that may not be readily available at site level.

Specific concerns raised included:

- Equipment that relies on high-energy systems requiring electromagnetic shielding or custom power supplies
- New inspection routines and maintenance practices for dynamic or non-traditional breakage mechanisms
- Limited interoperability with existing control systems or plant-wide DCS/PLC architectures
- Higher dependency on vendor support due to lack of operational maturity

Participants agreed that even conceptually elegant solutions may falter in practice if they demand skills or safety postures far outside the comfort zone of current plant operators.

C. DRY CIRCUIT IMPLICATIONS

Technologies designed for dry or near-dry operation introduce a unique set of operability trade-offs. While they offer benefits such as reduced slurry handling, lower reagent use, and simplified water circuits, they also create new maintenance and monitoring demands.

Examples discussed included:

- The need for robust dust control systems to ensure worker safety and protect equipment
- Higher wear rates in dry transport systems and classifiers due to abrasive particle movement
- Temperature build-up in enclosed systems, requiring heat dissipation solutions
- Tighter tolerances on particle size distribution to ensure circuit stability without the damping effect of water

Dry circuits also often demand tighter particle size control, which may place more pressure on screening and classification units. Participants also noted that success in dry flowsheets will depend not just on equipment design but on whole-of-system coordination.

D. MAINTAINABILITY OF COMPLEX OR UNPROVEN DESIGNS

A subset of technologies was viewed as particularly challenging from a maintainability standpoint due to design novelty or lack of operational data. These include systems with high-pressure fluids, thermodynamic phase shifts, or fine mechanical tolerances—all of which introduce challenges unfamiliar to most plant teams.

Concerns raised by the group included:

- Erosive or cavitation-related wear in fluid-based systems with narrow internal geometries
- Inspection, leakage, and integrity management in high-pressure gas circuits
- Dependence on proprietary components or external service providers for critical maintenance
- Unknown failure modes or maintenance intervals due to limited operational history

Participants highlighted the need for early-stage field validation not only of performance, but of maintainability, component longevity, and the practicality of real-world service cycles.

E. OPERATIONAL INTERFACE AND CONTROL

In addition to mechanical and process integration, operability was strongly associated with digital interface quality. Technologies with simple, intuitive human-machine interfaces (HMI), built-in diagnostics, and plug-and-play control modules were rated more positively than those requiring bespoke integration or intensive calibration.

Best practices identified included:

- Compatibility with existing control systems and remote monitoring capabilities
- Standardized protocols for fault detection, diagnostics, and safety shutdown
- Modular, transportable system architectures that simplify commissioning and relocation
- Interface designs that facilitate training and reduce dependency on vendor specialists

Participants emphasized that even highly automated systems must prioritize **operator trust and ease of use**, especially in remote or high-turnover environments.

F. STRATEGIC INSIGHTS

This group's discussion reinforced a practical truth: no technology, regardless of theoretical efficiency, will survive long in the field if it breaks down often, is hard to repair, or scares the operators.

Key insights included:

- **Operability and maintainability are key determinants of success at scale**, regardless of a technology's theoretical advantages.
- **Operational simplicity enhances resilience**, particularly in remote sites with limited engineering support or high workforce turnover.
- **Technologies that reduce complexity in one domain**—such as removing media or simplifying slurry circuits—must not introduce greater complexity in another.
- **Cultural fit and training demands** are often underestimated. Technologies requiring significant behavior change, new safety frameworks, or specialist-only maintenance may struggle to gain traction, even when performance is compelling.

7. THEME: THROUGHPUT AND METALLURGICAL PERFORMANCE

Comminution is not an end in itself—its ultimate value lies in how it affects mineral liberation, downstream recovery, and plant-wide productivity. The group responsible for evaluating throughput and metallurgical performance focused on how each technology influences material handling capacity, particle size distribution, and the efficiency of subsequent separation processes (liberation or exposure) such as flotation or leaching.

Their assessment emphasized that bigger isn't always better: a technology that increases throughput at the expense of liberation or product quality may reduce overall plant performance. Conversely, even moderate capacity machines may unlock value if they improve liberation or allow for more aggressive early rejection of gangue.

A. HIGH-THROUGHPUT TECHNOLOGIES WITH STABLE PERFORMANCE

Several technologies were acknowledged for their ability to consistently handle high material volumes while maintaining control over particle size distribution and circuit stability. These solutions were seen as reliable building blocks for base-load comminution, particularly in high-tonnage operations.

Key attributes identified included:

- Stable performance under variable ore types and moisture levels
- Controlled generation of fines to prevent downstream bottlenecks
- Capacity for integration into both wet and dry flowsheets

While high throughput alone was not deemed sufficient, participants recognized that these technologies can act as anchors for circuit redesign, especially when paired with newer liberation-focused or classification-enhanced modules.

B. LIBERATION-ORIENTED INNOVATIONS

A second category of technologies prioritized selective breakage and mineral exposure over sheer tonnage. These solutions target the root of metallurgical performance—liberating valuable minerals in a manner that maximizes recovery while minimizing energy input and tailings volume.

Technologies in this class often exhibit:

- Grain-boundary breakage or matrix-selective weakening
- The ability to liberate at coarser particle sizes
- Reduction in overgrinding, leading to better flotation kinetics or leach selectivity

Participants emphasized that true metallurgical value lies in the quality of breakage, not just its extent. In complex or low-grade ores, where overgrinding introduces costly penalties, selective liberation technologies were seen as pivotal to next-generation plant strategies.

Some of the most promising technologies from a metallurgical value standpoint were not the ones with the highest raw throughput, but those that enable selective breakage or grain-boundary liberation—leading to better recovery in flotation or leaching.

C. TECHNOLOGIES WITH UNCERTAIN OR VARIABLE IMPACT

Some technologies discussed presented inconclusive or highly variable performance profiles. In these cases, a lack of transparent data or operational history made it difficult to assess their true metallurgical or throughput implications.

Concerns noted included:

- Excessive fines generation leading to tailings dewatering or flotation challenges
- Ambiguity around throughput consistency under changing ore conditions
- Insufficient liberation or particle control metrics to support commercial decisions

The group reiterated that claims of high selectivity or novel breakage must be backed by empirical evidence—including pilot testing, mineralogical liberation mapping, and circuit integration studies.

D. ENABLING COARSE PARTICLE FLOTATION AND PRE-CONCENTRATION

A key area of focus was the alignment between comminution outputs and emerging beneficiation strategies, particularly coarse particle flotation (CPF) and early gangue rejection.

Technologies that help preserve particle size while enabling liberation were seen as critical enablers of:

- Reduced energy consumption, by minimizing unnecessary grinding
- Improved tailings behavior, through coarser and more filterable outputs
- Higher recovery per unit of energy and water used, by optimizing upstream breakage for downstream separation

Participants discussed how the shift to CPF-compatible comminution may alter design priorities entirely—placing greater value on micro-cracking, surface exposure, and fracture predictability over conventional throughput maximization. These approaches open the door to early gangue rejection, reduced water and reagent use, and shorter flotation residence times, all of which contribute to higher circuit efficiency and lower cost per tonne of metal produced.

E. KEY INSIGHTS AND RECOMMENDATIONS

The group concluded with several strategic reflections:

- Liberation quality matters more than particle size alone. Coarser particles can be floated or leached effectively if properly liberated.
- High throughput must be matched with control: excessive fines or variable size distributions can overwhelm downstream circuits.
- Next-gen comminution must be evaluated in terms of its total metallurgical contribution, not just breakage efficiency.

Participants proposed that future CEEC efforts could include quantitative liberation benchmarking alongside energy and water curves—potentially using standardized image analysis, flotation testing, or mineralogical modeling.

Ultimately, the group underscored that the next wave of successful comminution technologies will be those that help answer one simple question: how much more metal can we recover, with fewer passes, less energy, and cleaner tailings?