REMUNOM
ISSN 2178-6925

Received: 10/11/2026 - **Accepted:** 15/11/2026
Vol: 13.24
DOI: 10.66104/6m6bwj36
Pages: 1-30

ESTRATÉGIAS PARA A REDUÇÃO DO CONSUMO ENERGÉTICO NA COMINUIÇÃO MINERAL: TECNOLOGIAS, PRÉ-TRATAMENTOS E OTIMIZAÇÃO DE CIRCUITOS

STRATEGIES FOR REDUCING ENERGY CONSUMPTION IN MINERAL COMMINUTION: TECHNOLOGIES, PRETREATMENTS, AND CIRCUIT OPTIMIZATION

ESTRATEGIAS PARA REDUCIR EL CONSUMO ENERGÉTICO EN LA CONMINUCIÓN DE MINERALES: TECNOLOGÍAS, PRETRATAMIENTOS Y OPTIMIZACIÓN DE CIRCUITOS

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REMUNOM
ISSN 2178-6925

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Resumo

As operações de britagem e moagem devem proporcionar liberação mineral suficiente, limitando o consumo de eletricidade, a geração desnecessária de finos e o processamento de material estéril. Esta revisão narrativa examina tecnologias de cominuição energeticamente eficientes, pré-tratamentos de minérios e otimização de circuitos, com base em estudos experimentais, em escala piloto, industriais e de modelagem disponíveis até 12 de novembro de 2026. Rolos de moagem de alta pressão, moinhos de rolos verticais e moinhos de meios agitados apresentam oportunidades distintas conforme a alimentação, a granulometria requerida e a configuração do circuito. Micro-ondas, aquecimento convencional, pulsos de alta tensão e ultrassom podem modificar o comportamento de fragmentação, mas melhorias na moabilidade não asseguram um balanço energético favorável. As comparações quantitativas são interpretadas considerando os limites energéticos, as especificações dos produtos e as escalas dos estudos. Classificação, seleção dos corpos moedores, rejeição antecipada de ganga e controle integrado podem reduzir a moagem desnecessária e complementar mudanças de equipamentos. O critério de seleção mais consistente é a energia necessária para obter um produto metalurgicamente adequado a partir de uma quantidade definida de alimentação original, incluindo pré-tratamentos e cargas auxiliares. A adoção de tecnologias emergentes requer ensaios contínuos, variabilidade mineralógica representativa e balanços transparentes de massa, energia e recuperação.

Palavras-chave: processamento mineral; energia específica; rolos de moagem de alta pressão; pré-tratamento de minérios; moagem em meios agitados; otimização de circuitos.

Abstract

Crushing and grinding must provide sufficient mineral liberation while limiting electricity consumption, unnecessary fines generation, and the treatment of barren material. This narrative review examines energy-efficient comminution technologies, ore pretreatments, and circuit optimization using experimental, pilot-scale, industrial, and modelling studies available by 12 November 2026. High-pressure grinding rolls, vertical roller mills, and stirred media mills offer different opportunities according to feed characteristics, required product size, and circuit configuration. Microwave irradiation, conventional heating, high-voltage pulses, and ultrasound can alter breakage behaviour, but improvements in grindability do not necessarily produce a positive process energy balance. Quantitative comparisons are therefore interpreted using their original energy boundaries, product specifications, and evidence scales. A copper-ore vertical roller mill study reported an 18% specific-energy reduction, whereas pilot microwave work supported simulated comminution reductions of up to 9% at a specified plant grind. These outcomes cannot be ranked directly. Classification, grinding-media selection, early gangue rejection, and coordinated process control can reduce avoidable grinding and complement equipment changes. The most defensible selection criterion is the energy required to obtain a metallurgically acceptable product from a defined quantity of original feed,

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including pretreatment and auxiliary loads. Wider adoption of emerging technologies requires continuous trials, representative ore variability, and transparent mass, energy, and recovery balances.

Keywords: mineral processing; specific energy; high-pressure grinding rolls; ore pretreatment; stirred milling; circuit optimization.

Resumen

Las operaciones de trituración y molienda deben proporcionar una liberación mineral suficiente, limitando el consumo eléctrico, la generación innecesaria de finos y el procesamiento de material estéril. Esta revisión narrativa examina tecnologías de conminución energéticamente eficientes, pretratamientos de minerales y optimización de circuitos mediante estudios experimentales, a escala piloto, industriales y de modelización disponibles hasta el 12 de noviembre de 2026. Los rodillos de molienda de alta presión, los molinos de rodillos verticales y los molinos de medios agitados ofrecen oportunidades diferentes según la alimentación, el tamaño requerido del producto y la configuración del circuito. Las microondas, el calentamiento convencional, los pulsos de alta tensión y los ultrasonidos pueden modificar la fragmentación, pero una mejor molturabilidad no garantiza un balance energético favorable. Las comparaciones cuantitativas consideran los límites energéticos, las especificaciones de los productos y las escalas de los estudios. La clasificación, la selección de medios de molienda, el rechazo temprano de ganga y el control integrado pueden reducir la molienda innecesaria. El criterio de selección más consistente es la energía necesaria para obtener un producto metalúrgicamente adecuado a partir de una cantidad definida de alimentación original, incluyendo pretratamientos y equipos auxiliares. La aplicación de tecnologías emergentes requiere ensayos continuos, variabilidad mineralógica representativa y balances transparentes de masa, energía y recuperación.

Palabras clave: procesamiento de minerales; energía específica; rodillos de molienda de alta presión; pretratamiento de minerales; molienda con medios agitados; optimización de circuitos.

1. Introduction

Comminution establishes the particle sizes and mineral exposure on which subsequent concentration depends. Its purpose is not simply to make smaller particles: it is to prepare an ore for separation with acceptable recovery, selectivity, and throughput. Because valuable minerals occur in different associations and grain sizes, this preparation can require several crushing, primary grinding, and regrinding stages. The energy needed is consequently controlled by both the

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resistance of the material and the degree of liberation demanded by the flowsheet. A circuit processing a finely disseminated ore cannot be assessed against a coarsely liberated ore on electricity consumption per tonne alone.

The industrial importance of this distinction is illustrated by the copper and gold benchmarking study of Ballantyne and Powell. Their analysis considered ore competence, grind size, circuit efficiency, and grade, showing that the basis used to express energy intensity changes how operations are compared. In particular, energy per unit of valuable production introduces the effects of grade and recovery that are absent from an ore-tonnage denominator (Ballantyne and Powell, “Benchmarking”). Benchmarking can identify an inefficient operating regime, but an apparently high energy intensity may also reflect a difficult mineralogical duty. Meaningful improvement therefore requires a reference that describes both the input material and the intended product.

Equipment development has expanded the available routes beyond conventional tumbling mills. Particle-bed compression in high-pressure grinding rolls and the concentrated stressing environments of stirred mills provide alternatives for suitable size ranges. Nevertheless, the efficiency of a breakage mechanism and the efficiency of a complete plant are different questions. Feed preparation, classification, pumping, material transport, and drying may determine whether a favourable machine-level comparison survives circuit integration (Schönert; Taylor et al.). Existing installations also retain substantial opportunities through operating adjustments and reduced recycling of finished material (Jankovic and Valery, “Closed Circuit”).

Pretreatment introduces a further possibility: changing the ore before mechanical breakage. Selective heating or electrical discharge can create defects that facilitate fracture, while thermal treatment and ultrasound can affect grain boundaries, existing cracks, or particle aggregates. Reviews document a broad range of responses but also persistent barriers associated with energy input and scale-up (Adewuyi et al.; Singh et al.). A reduction in a grindability index is useful evidence of altered material behaviour; it does not establish that the electricity saved downstream exceeds the energy supplied to the treatment.

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The contribution of this review is to connect these alternatives through a consistent interpretation of energy, product quality, and evidence scale. Technologies are compared through their mechanisms and reported applications without assigning a universal ranking to percentages obtained under different conditions. The objective is to critically assess equipment selection, ore pretreatment, and circuit optimization as strategies for reducing specific comminution energy while preserving the required granulometric and metallurgical performance.

2. Literature Review Methodology

This narrative review used targeted web searches of scholarly literature, publisher article pages, and institutional repositories, complemented by Crossref metadata checks. Sources consulted included ScienceDirect, Springer, Taylor & Francis, MDPI, OneMine, and university repositories. Searches combined “comminution” or “grinding” with “specific energy,” “energy efficiency,” “HPGR,” “vertical roller mill,” “stirred mill,” “microwave pretreatment,” “thermal pretreatment,” “high-voltage pulses,” “ultrasound,” “classification,” “ore sorting,” and “process control.” The review considered publications available up to 12 November 2026, including recent studies and earlier contributions relevant to established principles and technological development. The selection was targeted and thematic, without seeking exhaustive coverage of the literature.

Selection favoured mineral-processing studies reporting a defined material, operating context, energy indicator, or mechanism directly relevant to crushing and grinding. Experimental and industrial investigations were prioritized for performance comparisons. Reviews were used to establish context and identify research gaps. Bibliographic titles, authors, publication data, and DOI correspondence were checked against publisher or registration records. The final bibliography comprises 44 references. Experimental, pilot-scale, industrial, and modelling studies were used to discuss technological performance, while review articles provided supporting context.

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The synthesis is thematic and comparative, not systematic or bibliometric. No pooled energy-saving estimate was calculated. Laboratory measurements, pilot trials, plant surveys, and simulations are identified separately. Percentages are retained on their original bases, and reductions in work index, grinding energy, total circuit energy, and energy per recovered product are distinguished. Missing auxiliary-energy or recovery data are treated as limits on interpretation; assumed values are not substituted.

3. Energy Consumption in Mineral Comminution

Mechanical fragmentation requires stresses sufficient to initiate or propagate cracks, but the electrical energy supplied to a machine also sustains motion, friction, deformation, and fluid flow. Consequently, the apparent efficiency depends on the chosen useful output. Surface-energy-based calculations and comparisons with single-particle fracture do not give the same numerical efficiency. Fuerstenau and Abouzeid showed why reference-state selection is fundamental when evaluating ball milling; Tromans further examined the physical limitations associated with fracture and energy dissipation (Fuerstenau and Abouzeid; Tromans). Very low surface-creation efficiencies should therefore not be interpreted as proof that nearly all plant electricity can practically be recovered by a simple equipment change.

Ore competence is also more complex than mineral hardness. Grain boundaries, cleavage, pre-existing defects, mineral distribution, porosity, and particle size determine the stresses required for fracture. A hard mineral embedded in a weak matrix may be liberated without extensive breakage of the mineral itself. Conversely, finely intergrown phases may demand substantial size reduction even when bulk rock strength is moderate. This distinction explains why a change in breakage mechanism can affect liberation differently from its effect on size distribution. Comparative testing on magnetite-rich material using a superfine crusher and high-pressure grinding rolls explicitly combined energy-size indicators with mineralogical evaluation (Baawuah et al.).

The classical energy-size relationships provide useful descriptions within

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restricted operating domains. Kick's formulation relates energy to the logarithm of a size-reduction ratio and is commonly associated with relatively coarse reduction. Rittinger's formulation relates energy to newly generated surface area, giving greater weight to fine grinding. Bond's empirical relationship occupies a central position in conventional grinding design and connects specific energy to the inverse square roots of feed and product characteristic sizes (Bond). These descriptions are not competing universal constants: their applicability depends on the material, size interval, breakage environment, and calibration procedure.

In the commonly used Bond expression, $E = 10\ W_i(1/\sqrt{P_{80}} - 1/\sqrt{F_{80}})$, F_{80} and P_{80} are the sizes through which 80% of feed and product pass, expressed in micrometres. E and W_i must use the same mass basis. Historical short-ton and metric-ton work-index conventions require attention during comparison. W_i is an empirical resistance parameter derived from a specified test; it is not the measured consumption of every circuit treating that ore. Changes in closing screen, feed preparation, or product distribution can affect the inferred benefit of a pretreatment. Work on high-pressure grinding products specifically identifies the difficulty of interpreting conventional Bond tests when feed properties have been modified (Ballantyne et al., "Improved Characterisation").

Specific energy is electrical or mechanical energy divided by a stated mass. For a steady process, power divided by mass flow yields kWh/t when compatible units are used. Gross electrical input, net shaft input, and net breakage energy differ because they include different losses. Total circuit energy is the sum of loads within an explicitly defined boundary. Energy efficiency requires an additional reference to useful performance, such as a target size distribution, adequate liberation, or recovered mineral output. Using these expressions interchangeably conceals changes in the duty and may favour a technology merely because its auxiliary loads were excluded.

Fine grinding adds another complication: particles are increasingly difficult to capture and stress effectively, while slurry rheology and agglomeration can influence energy transfer. Stirred-mill investigations connect the useful stress

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intensity to grinding-media size, density, and velocity, together with the frequency of stressing events (Kwade; Becker et al.). Increasing the energy of each collision is not necessarily productive if it greatly exceeds the requirement for the remaining particles. Conversely, many contacts that are too weak to cause fracture consume energy without achieving the target product. Efficient operation matches the stressing environment to the changing feed.

The plant objective should therefore specify a product distribution and metallurgical constraint, not only P_{80}. Two products with equal P_{80} may contain different coarse tails, ultrafine fractions, shapes, and liberation distributions. A circuit that reduces its mean energy while producing more unliberated coarse particles may transfer a penalty to flotation or leaching. A circuit that achieves equivalent recovery at a coarser product may legitimately save energy through a changed separation duty. These are distinct comparisons and should be reported separately. Two comparison scenarios should be distinguished: equivalent particle size distributions with comparable metallurgical performance, and different particle size distributions that achieve equivalent metallurgical performance. In both cases, throughput, recovery, and selectivity should be considered, together with the proportions of coarse and ultrafine particles when available.

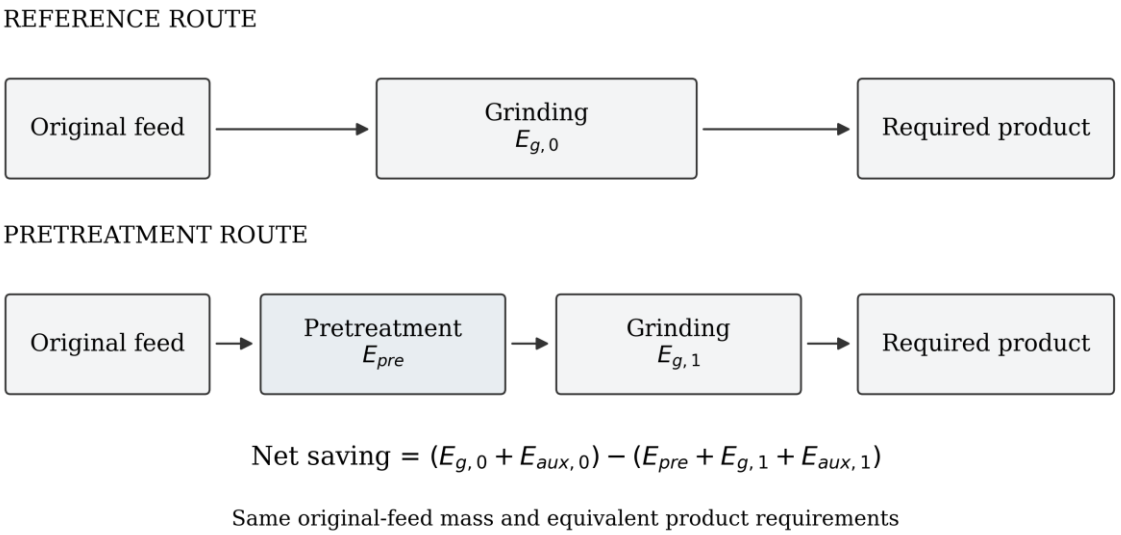
Figure 1 presents the energy boundaries used in this review. The diagram distinguishes the local grinding comparison from the full route, with every energy input normalized to the same original-feed mass.

Figure 1. Energy accounting for untreated and pretreated comminution routes.

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The figure shows why ore weakening alone is insufficient to demonstrate a positive balance. For matched throughput and product quality, the treatment route is favourable only when the reduction in downstream and auxiliary consumption exceeds its additional treatment demand. If mass is removed before grinding, the retained mass fraction must also enter the calculation. This accounting framework permits comparisons between technologies while retaining the distinctions between their mechanisms.

4. Energy-Efficient Comminution Technologies

High-pressure grinding rolls compress a confined particle bed between counter-rotating rolls. The dominant stressing environment differs from the distributed impact and abrasion in tumbling mills. The early work of Schönert established particle-bed compression as a route for improving comminution performance and provided the basis for subsequent industrial development (Schönert). Its advantages depend on maintaining an effective bed and balancing pressure, throughput, feed distribution, and product requirements. Increasing pressure can generate a finer product, but the extra roll energy must be justified by

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the downstream energy reduction.

Morrell's circuit-design analysis relates high-pressure grinding performance to sizing and operating conditions and identifies lower specific grinding forces as potentially favourable for energy efficiency (Morrell). This is a useful counterpoint to the assumption that maximum pressure necessarily gives the best flowsheet. Roll geometry, feed moisture, edge effects, wear, and recycling influence the operational result. A project-level comparison should include crushing and screening required to prepare the roll feed and the treatment of compacted product. Savings attributed to the downstream ball mill cannot be credited without the corresponding roll and auxiliary energy.

Potential microcracking in high-pressure products must also be separated from the straightforward benefit of a finer mill feed. If the treated material enters a ball mill with a different size distribution, lower milling consumption may arise even without a change in intrinsic resistance. The study on improved characterization of high-pressure grinding products emphasizes this measurement problem (Ballantyne et al., "Improved Characterisation"). A defensible comparison reports feed distributions and test preparation, then evaluates the complete energy-size trajectory. Assigning all downstream benefit to microcracks can overstate the contribution of pre-weakening and distort circuit optimization.

Dry high-pressure grinding coupled with air classification can extend particle-bed breakage into duties otherwise assigned to mills. Jankovic and co-authors compared a closed air-classified configuration with a screened high-pressure route followed by Bond grinding tests using aggregate material (Jankovic et al., "Evaluation of Dry Grinding"). This design illustrates the importance of integrating the separator with the breakage device. Its transfer to a wet mineral-processing plant requires a separate assessment of air movement, dust handling, moisture, and subsequent slurry preparation. A successful dry test does not establish that replacing a wet circuit will reduce total energy under a different climate or feed-water condition.

Vertical roller mills also use compression of a particle bed, with grinding, classification, and potentially drying integrated into one installation. In mobile pilot

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tests on chalcopyrite ore, the reported specific-energy requirement was 18% lower than that of the existing rod-and-ball milling circuit (Altun et al., “Copper Ore Grinding”). The relevance of this result is its comparison with a defined plant duty; the percentage is not a general value for all copper ores. Air-swept and overflow operation involve different material and gas handling, which must remain within the selected comparison boundary.

For iron ore, Reichert and co-authors investigated two magnetite ores in a pilot vertical roller mill and used experimental design to quantify operating effects. Their findings included higher magnetite liberation than in a conventional pebble mill (Reichert et al.). Liberation evidence strengthens a technology comparison because it tests whether a size-based advantage is metallurgically relevant. A separate investigation of gold-ore grinding showed that working pressure and classifier rotor speed interact in determining product size and production rate (Altun et al., “Operational Parameters”). These studies favour ore-specific optimization over transferring operating settings directly from cement practice.

Stirred media mills are especially relevant when small media and frequent particle contacts are required. The vessel may be vertical or horizontal, and the media motion may be dominated by gravity or by a strongly fluidized stressing environment. “Vertical” therefore does not identify a single mechanism or guarantee an energy advantage. Jankovic’s experimental studies examined mill design, media, speed, and slurry density, demonstrating the need to consider these variables together (Jankovic, “Variables Affecting”; Jankovic, “Media Stress Intensity”). Selecting a mill family without selecting the media and operating window leaves much of its potential efficiency undefined.

Stress-intensity analysis explains why finer grinding can benefit from smaller media: more stressing events become available for a given media volume, while contact energies can better match the smaller particles. Media that are too small, however, may fail to break the coarse feed. Kwade’s work and the subsequent analysis with co-authors connect these effects to specific-energy demand (Kwade; Becker et al.). A practical sequence may therefore use coarser media or another machine for initial reduction, followed by smaller media for the final liberation duty.

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The transition size must be established through testing.

De Bakker's synthesis of fine-grinding research and operating experience identifies media quality, size, and operating conditions as major determinants of consumption (de Bakker). This means that a poorly optimized stirred mill should not be treated as a representative benchmark for the technology. Media wear introduces further considerations: replacement cost, contamination, product chemistry, and the evolution of the charge distribution. Taylor and co-authors also emphasize the limitations of applying conventional grindability and energy-size relationships indiscriminately to stirred milling (Taylor et al.). Testing should reproduce the actual fine-grinding duty as closely as practical.

Hybrid configurations seek to use each mechanism where it is most effective. Experimental work on low-grade platinum-group-element-bearing chromite ore found the high-pressure-roll/stirred-mill combination more energy efficient than the high-pressure-roll/ball-mill alternative under the investigated conditions (Santosh et al.). The result supports testing such combinations for ores requiring extensive size reduction. It does not imply that a stirred mill can accept any high-pressure product without an intermediate preparation stage. The appropriate feed top size, slurry conditions, and classification remain critical to successful integration.

Table 1 summarizes the mechanisms and application limits of the main equipment options. Numerical evidence is retained only for a defined comparison; the remaining entries explain why testing is needed before assigning a saving.

Table 1. Energy-efficient comminution technologies and conditions governing their application.

Technology and mechanism	**Evidence and application**	**Main qualification**
High-pressure grinding rolls; particle-bed compression	Ore-specific force and circuit design (Schönert; Morrell)	Include feed preparation, recirculation, wear and downstream grinding.
HPGR with air classification	Comparative dry aggregate grinding tests (Jankovic et al., "Evaluation of Dry Grinding")	Air-handling energy and feed moisture govern transfer to ore circuits.

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Vertical roller mill; compressed bed and integrated classification	Copper-ore pilot comparison: 18% lower specific energy (Altun et al., “Copper Ore Grinding”)	Result refers to the evaluated rod/ball reference circuit.
Vertical roller mill for magnetite	Pilot evidence of improved liberation (Reichert et al.)	Liberation benefit does not quantify net circuit saving.
Stirred media mills; frequent controlled stressing	Fine-grinding studies and operating experience (de Bakker; Jankovic, “Variables Affecting”)	Select media, speed and rheology for actual feed and product.
HPGR followed by stirred milling	Favourable experimental comparison for PGE-bearing chromite (Santosh et al.)	Feed top size and circuit transitions require testing.

The table indicates that the strongest reason to choose an alternative machine is a match between its stress environment and the required duty. Compression technologies can reduce the burden on later grinding, while stirred mills can improve the use of energy at fine sizes. These benefits are complementary, but a hybrid circuit must be evaluated as a complete system, including the transitions between dry and wet operation and the removal of already-finished particles

5. Ore Pretreatment Strategies

Pretreatment aims to alter the material response before the principal mechanical reduction. Potential mechanisms include differential thermal expansion, internal electrical breakdown, weakening of grain boundaries, and propagation of existing defects. The relevant question is whether the modification reduces the energy required to produce an equivalent useful product. Reviews by Singh and co-authors and Adewuyi and co-authors show that the techniques differ substantially in maturity and in the completeness of their energy accounting (Singh et al.; Adewuyi et al.). The following comparisons therefore distinguish mechanical weakening from a demonstrated net-energy benefit.

Microwave treatment generates heat through interactions between the electromagnetic field and absorbing phases. Differential absorption and thermal expansion can produce stress concentrations at mineral interfaces. The distribution,

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grain size, and connectivity of absorbing minerals matter as much as their bulk abundance. Kingman, Vorster, and Rowson demonstrated that mineralogy influences the change in work index after irradiation (Kingman et al., “The Influence of Mineralogy”). This dependence makes a bulk temperature alone an incomplete treatment descriptor: two samples at the same mean temperature may have experienced very different local gradients and fracture histories.

Work on Neves Corvo copper ore further linked microwave exposure to subsequent processing response, reinforcing the need to combine grindability and mineralogical observations (Vorster et al.). Selectivity is particularly important because the goal is often to open interfaces around valuable grains without grinding all phases to the same fine size. Yet micrographs showing cracks are not a direct measure of usable energy saving. Defects must affect the material entering the relevant mill, survive handling, and improve the required product at a measurable energy cost.

High power applied for a short residence time can create more favourable local gradients than prolonged low-power heating. Kingman and co-authors reported reductions in required comminution energy exceeding 30% at microwave inputs below 1 kWh/t for a copper carbonatite ore (Kingman et al., “Recent Developments”). Their separate investigation used drop-weight testing to examine how applied power, cavity design, and energy transfer influenced breakage (Kingman et al., “An Investigation”). These results concern controlled laboratory responses and should not be interpreted as equivalent industrial electricity savings. In particular, an energy delivered to the microwave field is not automatically the electrical consumption at the supply connection.

Engineering scale-up has been demonstrated more directly in the pilot system described by Buttress and co-authors. It used two 100 kW generators operating at 896 MHz and a gravity-fed arrangement, with a throughput capability up to 150 t/h (Buttress et al.). This is important evidence that treatment need not rely exclusively on small batch cavities. It also shows why applicator geometry and material transport are part of the technology. A successful increase in throughput must retain sufficient and reasonably uniform treatment, without excessive reflected power or a

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distribution of residence times that leaves a substantial fraction untreated.

In the associated metallurgical investigation, Batchelor and co-authors examined low treatment doses and combined experimental characterization with flowsheet simulation. Simulated specific comminution-energy reductions reached 9% at P_{80} = 190 μm and 24% at P_{80} = 290 μm for microwave inputs of 0.7 to 1.3 kWh/t (Batchelor et al.). The two percentages correspond to different grind targets. They are neither additive nor interchangeable, and the simulations do not constitute an observed reduction in plant electricity. Their practical implication is that the treatment benefit depends strongly on the downstream duty; any net comparison still requires a consistent treatment-input and auxiliary-load boundary.

Conventional heating can also induce thermal stresses, but usually heats a larger fraction of the ore mass and surrounding equipment. Fitzgibbon and Veasey's early review identified thermally assisted liberation as a potentially useful approach while making clear that liberation and economic feasibility are connected questions (Fitzgibbon and Veasey). Heat may also cause phase transformations, oxidation, dehydration, or changes in surface chemistry. Consequently, improved grinding can coexist with adverse flotation response or altered separation selectivity. A thermal route needs to be tested with its intended downstream process, particularly when treatment temperatures are high enough to change mineral phases.

For high-phosphorus oolitic iron ore, Omran and co-authors observed more favourable grindability after microwave treatment than after conventional furnace treatment, together with differences in intergranular fracture development (Omran et al.). The comparison supports the relevance of selective heating and mineral texture. It does not provide a universal conversion between temperature, crack density, and grinding energy. Oolitic associations are structurally different from coarse porphyry ores, and the most favourable treatment for one association may not transfer to another. Matched-temperature comparisons also require caution because the heating rate and spatial temperature distribution can differ.

A particularly instructive energy limitation appears in the Chilean copper-ore study of Cisternas and co-authors. Heating between 300 and 600 °C produced a maximum reported work-index reduction of 19%. The estimated heat requirement

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REMUNOM
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to raise the sample from 25 to 600 °C was 37.48 kWh/t (Cisternas et al.). This energy term is not a measured full-furnace electrical balance. Nevertheless, it demonstrates that appreciable weakening can require a heat input large enough to undermine a grinding-only saving.

Using solar or recovered heat could change the electricity and cost balance of conventional heating, but would not eliminate the thermal demand. These quantities must be reported separately. Heat availability, transfer losses, storage, and the need to cool material before wet grinding affect implementation. Quenching may intensify damage through thermal shock, yet its water demand and heat rejection are additional process requirements. A treatment already required for another metallurgical purpose may justify a different allocation of energy, but the allocation must be explicit and should not be used to hide an added unit operation.

High-voltage pulses can create electrical breakdown paths and associated mechanical stresses within particles. Under suitable pulse and dielectric conditions, discharge through the solid can preferentially damage interfaces; discharge mainly through the surrounding liquid imposes a different loading mechanism. Wang, Shi, and Manlapig treated several ores at 1 to 3 kWh/t and reported downstream benefits reaching 24%, with different responses among ores (Wang et al., “Pre-weakening”). The energy supplied during pretreatment must be deducted from any subsequent saving. The result demonstrates ore-dependent pre-weakening, not a guaranteed 24% reduction for the complete route.

Their subsequent work examined operational and ore-related controls on electrical comminution, including the conditions governing discharge effectiveness (Wang et al., “Factors Affecting”). A further comparison at equal specific-energy levels found that electrical treatment could produce a coarser distribution with fewer fines than conventional comminution (Wang et al., “Mineral Liberation”). This result matters because a coarser product can still be useful if selective breakage improves liberation. Comparing only product fineness would overlook that possibility, whereas assuming equal liberation from similar size distributions would introduce the opposite error. Energy and liberation measurements should therefore be interpreted jointly.

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ISSN 2178-6925

Received: 10/11/2026 - **Accepted:** 15/11/2026
Vol: 13.24
DOI: 10.66104/6m6bwj36
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Shi, Zuo, and Manlapig proposed a pre-weakening index based on the change in a breakage-resistance indicator per unit of electrical treatment energy (Shi et al.). This addresses the need to separate ore amenability from machine settings. The experiments of van der Wielen and co-authors examine the influence of equipment settings and rock properties on high-voltage breakage (van der Wielen et al.). More recently, Zhang and co-authors examined breakdown-field behaviour, circuit parameters, and pulse polarity (Zhang et al.). Together, these studies indicate that generator voltage alone is insufficient to describe a treatment; pulse shape, delivered energy, electrode arrangement, water properties, and particle presentation influence the useful effect.

Ultrasound requires an equally careful definition of the process. Energy introduced into a liquid can induce cavitation and local stresses, but it can also disperse aggregates without fracturing primary mineral grains. Ultrasound imposed directly in a stressing zone represents another configuration. Gaete-Garretón and co-authors investigated ultrasound-assisted comminution and reported reduced torque and energy for equivalent grinding results (Gaete-Garretón et al.). This finding supports the possibility of beneficial coupling between acoustic and mechanical stresses, but it cannot be transferred directly to a separate ultrasonic bath or probe pretreatment. Acoustic attenuation, treated mass, and coupling efficiency must be established for each arrangement.

Table 2 compares selected pretreatment evidence with its energy interpretation. Results without a complete electrical balance are explicitly retained as local or proxy responses.

Table 2. Selected ore pretreatment results with their original energy interpretation.

Treatment and material	**Conditions and result**	**Energy interpretation**
Microwave; copper carbonatite (Kingman et al., “Recent Developments”)	Laboratory high-field treatment; input <1 kWh/t; >30% reduction in required comminution energy	Local test result.

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Microwave; porphyry copper (Batchelor et al.)	Pilot characterization with simulation: 0.7 to 1.3 kWh/t; up to 9% at P80 190 µm or 24% at 290 µm	Simulated comminution response at two distinct grind targets.
Furnace; Chilean copper (Cisternas et al.)	300 to 600 °C; up to 19% lower work index; estimated heating demand 37.48 kWh/t	Work index is a proxy; heat demand is not a full electrical balance.
Microwave versus furnace; oolitic iron ore (Omran et al.)	Microwave-treated material showed more favourable grindability	No complete route saving assigned.
High-voltage pulses; several ores (Wang et al., “Pre-weakening”)	1 to 3 kWh/t treatment; downstream benefit up to 24%	Deduct treatment and auxiliary demand; strong ore dependence.
Ultrasound-assisted comminution (Gaete-Garretón et al.)	Reduced torque and total energy for equivalent grinding	Coupled grinding evidence; not a separate pretreatment benchmark.

Note: The reported results involve different energy indicators and comparison boundaries. Information on auxiliary energy consumption, metallurgical recovery, and experimental uncertainty was not uniformly available for these comparisons. Consequently, the values should not be interpreted as directly comparable net energy savings.

The comparisons show that no single weakening indicator substitutes for a route balance. A lower work index, a higher breakage rate, and a reduced motor load are different observations. For batch tests, treatment power and time must be related to dry sample mass; for continuous systems, actual average throughput and delivered power are required. Where only nominal equipment power is available, the resulting dose should be labelled nominal and should not be presented as measured electricity consumption.

Chemical additives provide a related opportunity to influence grinding through dispersion, slurry rheology, and particle interactions. Their industrial relevance is established particularly in cement practice, but transfer to metallic ores requires checking the downstream reagent environment (Adewuyi et al.; Singh et al.). A grinding aid that reduces apparent viscosity or agglomeration may improve transport and effective stressing without generating internal cracks. Conversely, a

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reagent beneficial to grinding may interfere with flotation selectivity. Combined treatments should therefore be justified by incremental benefit over each component, including their additional energy and consumables. Maximum observed weakening alone is insufficient

6. Comminution Circuit Optimization and Process Integration

Energy-efficient operation begins with a clear description of where the existing circuit expends energy and where material unnecessarily returns for further grinding. Power, feed rate, size distributions, water addition, and circulating streams should be measured over a sufficiently stable interval. A lower kWh/t value obtained during unusually soft ore processing does not establish an operational improvement. Changes should be compared within representative ore domains or through a calibrated model that accounts for feed differences. The benchmarking framework of Ballantyne and Powell provides a useful basis for separating material duty from circuit performance (Ballantyne and Powell, “Benchmarking”).

Grinding-media selection is a direct operating lever. Large media provide higher individual stressing energies and may be required for coarse or competent feed, but can be inefficient once the remaining particles need more numerous lower-energy contacts. Small media can improve fine grinding while failing to break the coarse tail. The experimental studies of Jankovic and the stress-intensity framework of Kwade connect this trade-off to speed, media density, and solids conditions (Jankovic, “Variables Affecting”; Becker et al.). Media optimization should use the operating charge distribution, including wear. A fresh monodisperse laboratory charge may not reproduce a mature industrial mill.

Solids concentration affects both particle availability in the stressing zone and slurry transport. Excessive dilution expends pumping and mixing energy on water, while excessive viscosity may hinder media motion, classification, and discharge. The optimum is material- and equipment-dependent. Mill filling, speed, liner condition, and feed distribution similarly influence power draw and effective breakage. A lower mill power is beneficial only if the required tonnage and product

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REMUNOM
ISSN 2178-6925

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are maintained. Monitoring power without monitoring useful production can encourage an operating point that saves electricity per hour while increasing consumption per tonne.

Classification is central because finished particles should leave the grinding circuit promptly. Fines that bypass into the coarse return consume capacity and may undergo unnecessary further breakage. Jankovic and Valery revisited the interaction between classification efficiency and circulating load, showing why these variables cannot be optimized independently (Jankovic and Valery, “Closed Circuit”). A high circulating load is not automatically evidence of poor operation: efficient removal of finished particles can permit useful recirculation of coarse material. Conversely, increasing circulation through an inefficient classifier can mainly recycle fines and impose additional hydraulic demand.

A study combining circuit sampling and simulation investigated replacement of hydrocyclones with high-frequency fine screens and reported 13% higher throughput with 15% lower grinding energy in the evaluated comparison (Dündar). These values belong to that particular assessment. They should not be assigned to every screen installation or added directly to savings from another circuit modification. Screen capacity, aperture, water requirements, blinding, wear, and the feed-size distribution determine whether a similar improvement is attainable. The necessary comparison includes the entire classification and pumping arrangement.

Industrial surveys at the Vazante willemite plant provide a complementary type of evidence. Costa and co-authors compared hydrocyclone-only and hybrid screen–hydrocyclone configurations in two campaigns and found sharper separation with the hybrid arrangement (Costa et al.). Their particle-size and partition-curve results support the mechanism of reducing misplaced material. They do not, by themselves, establish an independently metered universal energy-saving percentage. The Brazilian case is valuable because it demonstrates classification behaviour under operating-plant conditions and highlights the need to connect size separation with downstream metallurgical performance.

Early rejection of barren material reduces the mass requiring the most energy-intensive size reduction. Lessard and co-authors studied ore sorting using

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REMUNOM
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experimental separation results and processing models, reporting potential milling-energy savings above 60% for favourable waste-rejection scenarios (Lessard et al., “Development of Ore Sorting”). This is a model-dependent opportunity, not a general plant result. Sorting is useful only where a discriminating signal corresponds sufficiently to valuable-mineral distribution at the sorting scale. Fine dissemination, surface contamination, particle overlap, and ore variability can reduce selectivity or require additional crushing before sorting.

The energy calculation should retain the original-feed denominator. If f is the retained dry-mass fraction, a simplified route balance is $E = E_{(}sorting_{)} + fE_{(}grinding,retained_{)} + E_{(}auxiliary_{)}$, with every term expressed per tonne of original feed after the appropriate conversion. This expression shows why reduced grinding mass can dominate the saving, but also why harder retained material may partly offset the benefit. The corresponding valuable-mineral recovery through sorting must be included in a product-based metric. Removing a large amount of mass is not successful preconcentration if it rejects an unacceptable proportion of the valuable component.

The later economic analysis by Lessard and co-authors extends sorting evaluation to its effects on the processing circuit (Lessard et al., “Bridging the Gap”). A mass reduction can release mill capacity, which the operator may use to treat more run-of-mine material. In that case, annual electricity consumption may remain similar while energy per unit of production falls. The distinction between absolute electricity demand and specific energy is essential for evaluating such projects. Preconcentration, equipment replacement, and finer control may create different operational benefits even when their headline percentages appear comparable.

Integrated control can stabilize operation near a useful operating envelope as ore properties and throughput change. Le Roux and co-authors developed and validated a grinding-circuit model for control applications, while later work used nonlinear model predictive control to coordinate throughput and product quality (le Roux et al., “Analysis and Validation”; le Roux et al., “Throughput and Product Quality”). These studies provide evidence for the modelling and control approach, not a transferable guaranteed energy saving. A controller should be evaluated

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REMUNOM
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against measured electricity, recovery constraints, and realistic disturbances. Simulation benefits require plant confirmation, particularly where sensors are biased or the feed changes outside the model calibration range.

Crushing and grinding should also be coordinated. Additional upstream reduction may improve mill throughput, but it consumes its own electricity and can alter screening loads or generate unwanted fines. The optimum transfer size occurs where the marginal upstream demand is justified by downstream benefit. High-pressure grinding, selective pretreatment, and preconcentration can all change that transfer point. This interaction means that separate unit-operation maxima should not be combined into a presumed optimum flowsheet. Table 3 summarizes operational measures and the observations needed to substantiate their effect.

Table 3. Circuit optimization measures and the evidence needed to verify energy benefits.

Measure	**Evidence or mechanism**	**Required comparison**
Media and operating adjustment (Jankovic, “Variables Affecting”; Becker et al.)	Match stress intensity and contact frequency to feed	Same product and throughput; representative worn charge.
Classification improvement (Jankovic and Valery, “Closed Circuit”; Dündar)	One sampling/simulation study reported 13% more throughput and 15% less grinding energy	Include separator and pumping loads; retain product constraints.
Hybrid screens and hydrocyclones (Costa et al.)	Sharper industrial classification at Vazante	Partition curves plus metered energy and metallurgical response.
Early gangue rejection (Lessard et al., “Development of Ore Sorting”; Lessard et al., “Bridging the Gap”)	Sorting models indicated >60% potential milling savings in favourable cases	Original-feed mass, valuable-mineral loss and retained-ore hardness.

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REMUNOM
ISSN 2178-6925

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Integrated process control (le Roux et al., “Analysis and Validation”; le Roux et al., “Throughput and Product Quality”)	Coordinate throughput and product quality under disturbances	Plant confirmation against an equivalent operating baseline.
Crushing–grinding integration (Morrell; Jankovic et al., “Evaluation of Dry Grinding”)	Redistribute reduction between efficient stages	Sum all stage energy; avoid double-counting downstream benefits.

The common feature of these measures is a reduction in unnecessary work: excessive stress intensity, grinding of already-finished particles, treatment of removable gangue, or unstable operation away from a suitable duty. Their benefits can overlap. For example, a better classifier changes the material population presented to the mill and may change the optimal media size. Sequential testing and a consistent baseline are therefore needed to avoid counting the same avoided grinding twice

7. Challenges and Future Perspectives

The principal comparability problem is the diversity of reported outcomes. Work-index reduction, breakage-rate increase, size-specific energy, net shaft energy, gross electricity, and energy per recovered metal answer different questions. A future dataset intended for cross-technology comparison should include feed and product distributions, ore mineralogy, liberation or recovery, dry mass, electrical metering points, and auxiliary loads. Uncertainty in these quantities should accompany the reported saving. A precise percentage derived from an uncertain mass flow or changing feed is not strong evidence of an equally precise improvement.

Scale-up must preserve the mechanism responsible for the benefit. For microwave treatment, greater throughput changes residence-time distribution and

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REMUNOM
ISSN 2178-6925

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electromagnetic loading. For high-voltage treatment, particle presentation and discharge pathways affect whether energy reaches the solid. For ultrasound, propagation and coupling change with slurry depth and solids loading. Pilot microwave engineering and the continuing work on electrical discharge parameters demonstrate that these are design variables, not merely corrections to a laboratory power setting (Buttress et al.; Zhang et al.). Continuous tests should include wear, fouling, downtime, and start-up behaviour because these affect annual specific consumption. Implementation also depends on water requirements, drying, material handling, feed variability, equipment availability, and possible effects on downstream separation.

Ore variability is another central limitation. A bulk composite can average together domains with very different thermal, dielectric, mechanical, and liberation responses. The same nominal treatment may overprocess one domain and underprocess another. A useful development programme should therefore combine mineralogical classification with response testing and mass-weighted production scenarios. The mineralogy-dependent microwave results and the variable response to electrical pre-weakening support this requirement (Kingman et al., “The Influence of Mineralogy”; Wang et al., “Pre-weakening”). Selective deployment to responsive material may be more effective than treating all feed at a dose chosen from the most favourable laboratory sample.

Economic and energy criteria also need separation. Higher recovery or throughput may make a technology profitable even when its energy balance is unfavourable. Conversely, a reduction in electricity may fail to recover the capital and maintenance cost of a new installation. Conventional heating supplied by low-cost or recovered heat could reduce purchased electricity without reducing total thermal demand. These are legitimate process-development objectives, but they should be described using the metric improved. Cost, carbon emissions, and physical energy consumption should not be represented by a single interchangeable saving percentage.

The evidence base would benefit from matched comparisons between technologies under common product constraints. Such tests should maintain

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REMUNOM
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representative feed sampling, quantify any treatment-induced change in feed size, and measure downstream recovery. Pretreatment sequences need untreated, single-treatment, and combined-treatment comparisons to establish incremental effects. A combined route is not justified solely because it gives the largest crack population. Its additional cost and energy must be assessed against the useful improvement beyond the simpler route, with uncertainty sufficient to distinguish a small real effect from experimental variation.

For operating plants, the most informative near-term trials are those that connect instrumented circuit surveys with an identifiable intervention. Classification changes, media adjustment, feed preparation, or control modifications can be assessed over comparable ore conditions before a larger equipment replacement is selected. Emerging pretreatments should then be judged against this optimized baseline, not against a deliberately poor conventional circuit. This approach narrows the industrial question to the additional benefit that remains after avoidable operating losses have been addressed.

8. Conclusions

Reducing comminution energy requires matching the breakage mechanism, feed characteristics, and classification arrangement to the intended mineral-separation duty. High-pressure grinding rolls, vertical roller mills, and stirred media mills offer complementary opportunities across different size ranges. The 18% reduction reported for a copper-ore vertical roller mill comparison illustrates a defined application; it is not a universal equipment advantage.

Ore pretreatments can improve breakage and liberation, but their local benefits must be distinguished from net process savings. Pilot microwave results supported simulations of up to 9% lower comminution energy at P_{80} = 190 µm, while electrical-pulse studies reported downstream improvements reaching 24%. Conventional heating also reduced work index, yet a copper-ore study estimated 37.48 kWh/t of heat demand, demonstrating the importance of accounting for the added treatment. These percentages and energy terms have different bases and cannot establish a technology ranking.

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REMUNOM
ISSN 2178-6925

Received: 10/11/2026 - **Accepted:** 15/11/2026
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Pages: 1-30

Classification, appropriate grinding media, early gangue rejection, and coordinated control can reduce avoidable grinding and complement equipment changes. Their benefits depend on the initial circuit and may overlap. The appropriate selection criterion is the energy needed to obtain an acceptable product from a defined original-feed mass, accompanied by recovery and throughput constraints. Continuous metering, representative ore variability, and complete route balances are essential to demonstrate whether laboratory or simulated improvements remain beneficial in practice.

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