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Mineral Processing

Mineral, renewable and secondary raw material processing – current engineering challenges

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» Comminution / Classification

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Table of Contents

1. Introduction

A country like Germany, which has a technology-based society and depends primarily on metalworking, machinery manufacturing, material science, chemicals, pharmaceuticals and semiconductor technology, requires a continuous flow of primary materials to sustain the value-add stream. From the end of the 1980s onwards, the supply of raw materials (i.e. exploration, extraction and processing of primary materials) has been steadily moving to the background of the economic and scientific policy agenda. Economic and geopolitical factors along with short-term considerations are the main reasons why that has been the case. We are talking here mainly about non-energy raw materials. As a result, the availability of affordable metallic raw materials such as ore concentrate in sufficient quantities has been taken for granted in most economic planning scenarios.

That being the case, R&D in the academic sector as well as resource allocation by German industry to related areas of research came to a virtual standstill over a period of nearly 25 years. Furthermore, the number of faculty departments dedicated to this particular field of endeavor at academic institutions which specialize in mining and earth sciences has declined, and some segments of the value-add chain can no longer be addressed. Also, the faculty departments involved have either specifically diverted their attention away from mining and earth sciences, or the same result was produced indirectly when faculty members began to prioritize other fields of research.

It has, however, become apparent over the past 5 years or so that the availability of mineral and metallic raw materials is now being driven by a different set of market fundamentals [23]. Rapid industrial growth in the emerging nations worldwide is putting considerable stress on the supplies of "timeless materials" such as copper, nickel and cobalt. New fields of technology and a general increase in the complexity of technical goods has driven up demand for raw materials which up until now have been available in sufficient quantities as by-products [21]. As a result of general economic growth and increased productivity worldwide, high-grade ore deposits (high concentration, low dissemination) can no longer satisfy demand, and that raises the visibility of complex deposits worldwide.

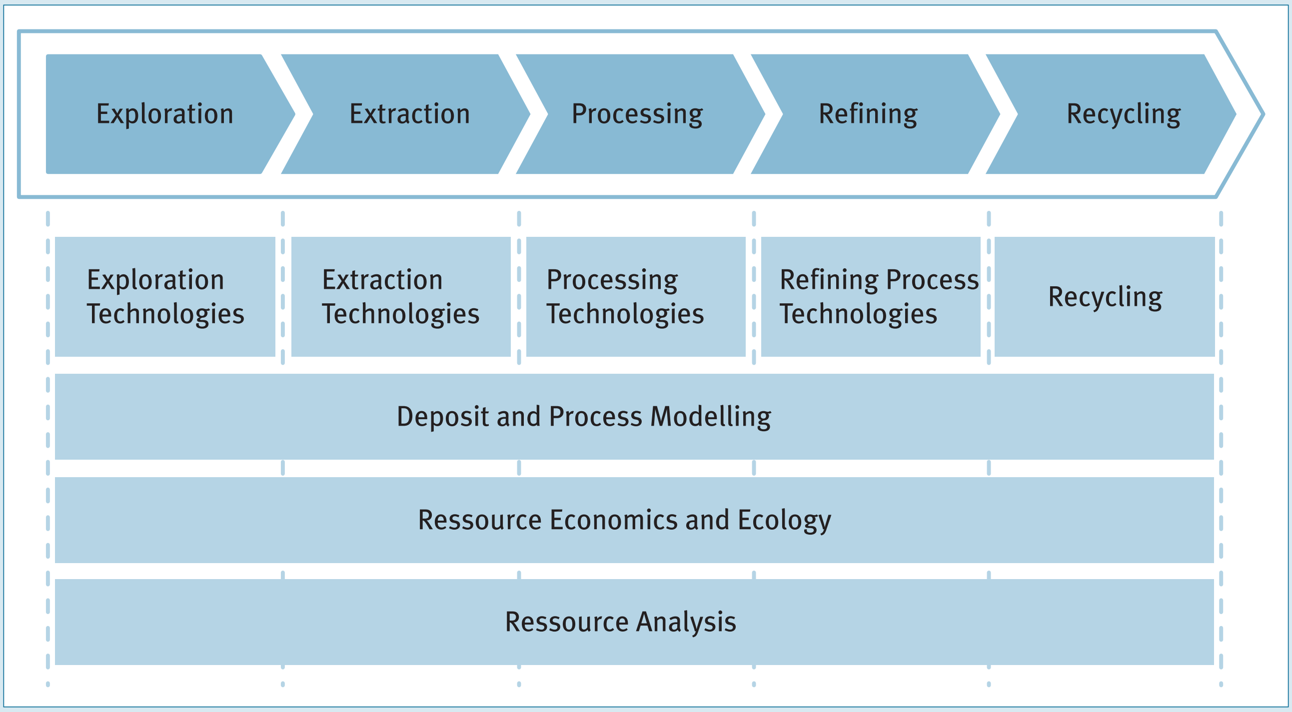

Fig. 1: Value chain for raw materials with cross-sectional scientific functions.
(after Helmholtz-Institut Freiberg für Ressourcentechnologie 2011, [16]).

From the technological standpoint, recycling cannot be excluded from the raw material supply debate. Although recycling alone cannot fully meet demand in a growth segment of industry, it is an important additional source for a variety of reasons. Among other things, recycling can be viewed as “urban mining” which provides a domestic and geopolitically secure source of raw material. In addition, material concentrations in recyclate often exceed that of the corresponding ore.

If you look at the historical trends in the process engineering departments at German universities in terms of department title and research profiles, you see a reflection of the structural change in the country’s industrial base. Since the 1960s, this transformation has however taken place without any abrupt discontinuities. The basic process engineering methods and consequently the core curriculum (more or less) have remained unchanged. The application aspects have reflected the “megatrends” over the years: chemical industry, environmental technology and recycling, fine chemical and pharmaceutical production, nanotechnology and biotechnology. Over this period, the process engineering R&D toolkit has retained its broad base of model generation, modeling and experimental techniques.

2. Processing Technology for Primary Resources

In the forward to the 2nd edition of his standard textbook *Aufbereitung fester mineralischer Rohstoffe* [13] Schubert from the TU Bergakademie Freiberg defines in 1975 mineral processing as follows:
"Mineral processing is the first step in the solid mineral extractive process. The goal is to produce granular material which meets a specific set of requirements in terms of material composition and physical characteristics (especially granulation). The minerals are then used either as is (e.g. potassium fertilizer, coal) or they pass through additional processing stages (metallurgy, chemical industry, construction industry, ceramics and glass industry, etc.). The extraction of secondary raw materials, especially metals, has increased significantly in recent years. The objective is to return valuable materials to the economic cycle in products which have suitable material composition and favorable physical properties."

Kellerwessel (Univ. of Stuttgart) added the following clarification in 1991 [12]:
"Originally, the term primary resource processing referred mainly to techniques for dressing raw materials obtained from mines. Such techniques are now classified as mechanical processing in contrast to metallurgical techniques where the value minerals are chemically altered, such as in the reduction of iron ore (iron oxide) to extract metallic iron, and also in contrast to conventional chemical processing."

Fig. 2 summarizes the mineral processing flow and the transition to the refining stage (hydrometallurgy). The goal of mechanical processing is to produce individual particles by comminution of ore which has a complex material composition. To the extent possible, these individual particles should have a homogenous material / mineral composition, meaning that they should be of only one type. This implies that the break should take place primarily at material transitions within the solid, i.e. at an ore's grain boundaries. Various physical and chemical sorting techniques can be used to separate the resulting mixture into concentrate (high ratio of the value mineral) and gangue. The yield and concentration of the value mineral are key criteria for production of the concentrate. The efficiency and selectivity of the sorting process determine

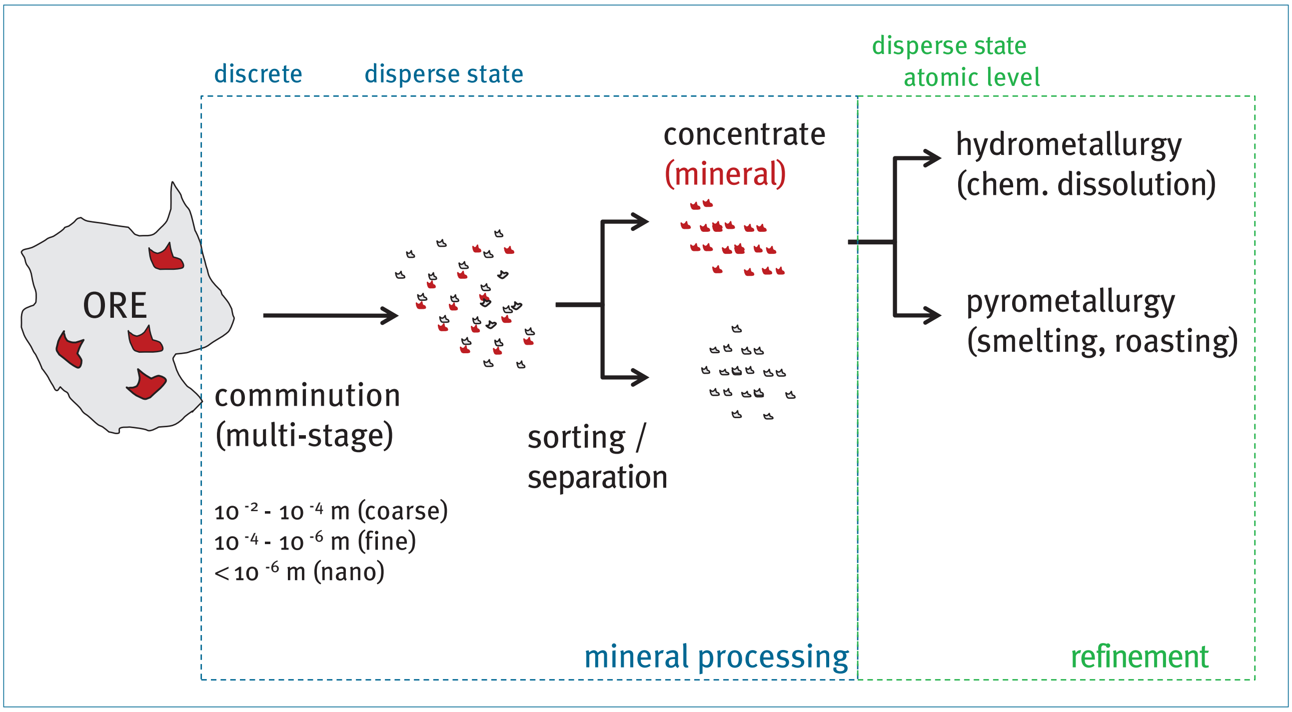

Fig. 2: Schematic representation of mineral processing. The same breakdown can also be applied to secondary and renewable raw materials, but the comminution classifications may be coarser.

the feasibility and cost-effectiveness of a mineral processing technique.

The concentration of the target element in the concentrate's target mineral is determined by the crystal stoichiometry. The crystalline structure has to be disturbed or broken down to remove the target element. Smelting, roasting and extraction to solution can be used to accomplish this. Extraction to solution plays a major role in mechanical mineral processing because mechanical liquid separation is a core technology in selective extraction as well as in recrystallization and precipitation, and it can determine the sustainability and yield of the process.

3. Common ground between mineral processing and mechanical process engineering

As the current process engineering disciplines have a direct root in the raw material and commodities industry, there is still a large amount of common ground between the two fields of technology, and that is particularly the case with mechanical processing. In the wake of structural change, process engineering tends to concentrate on whatever technology is at the forefront at any given time such as fine chemicals or biotechnology. As a result, a detailed understanding of ore and mineral material parameters and the size of the equipment needed to process them has eroded or disappeared altogether.

Ideally, a typical processing flow is divided into the following steps:

- Ore blending
- Crushing
- Pre-sorting
- Liberation / fine grinding
- Sorting
- Agglomeration, etc. of the concentrate
- Management of the residue (gangue, slurry, process fluids)

These steps can be viewed and described as macro mechanical process engineering operations.

The end product of mechanical mineral processing is an ore concentrate which is then put through a metallurgical process. Hydrometallurgy, pyrometallurgy or a combination of the two are used to “refine” the concentrate by detaching the atoms of the target elements from the crystal lattice at the atomic level. These metallurgical techniques have much in common with thermal process engineering, chemical engineering (crystallization, extraction and ion exchange) and mechanical process engineering (filtration, washing and membrane processes).

If you then also consider biohydrometallurgy, an alternative method for metal extraction, bioprocess engineering also becomes part of the equation. In the idealized view, mineral processing for bioleaching is divided into the following steps:

- Ore blending
- Crushing / Grinding
- Heap storage with defined permeability (heap leaching)
- Leaching through microorganism-ore interaction
- Regular repositioning
- Water management

Due to the extremely long investment cycles, the mining and mineral industry is very conservative when it comes to introducing new technology which represents a “quantum leap”. This also applies to mineral processing equipment which is normally located at the point of extraction. Production of concentrate significantly reduces the volume of material that needs to be transported.

The industries which are currently the main customers for process engineering R&D in Germany have been very willing to embrace new mechanical process engineering technology in recent years, with considerable success. This would indicate that in terms of their products these industries enjoy a technological advantage compared to mineral processing users. In addition, German manufacturers that supply solid mineral processing equipment have a lower market penetration in that particular segment than their counterparts which supply machinery to customers that operate further down the processing chain. From the mechanical and process engineering perspective, German mineral processing equipment suppliers belong to the world market elite (e.g. pressure filters for aluminum refineries, crushers for bituminous sand, high pressure grinding rolls and agitator ball mills for copper and platinum ore etc. and mixers and agglomerators for iron ore).

4. Technological/scientific challenges

The primary materials industry is currently in a transformation phase following a long period of low raw material prices which extended from the mid 1980s to the middle of the 1st decade of the current century. The slump in raw material prices resulted from political upheavals following the end of the Cold War. The Western industrialized nations and Germany in particular were able to obtain raw materials from sources that had previously been unavailable. Raw material intensive production in Eastern Europe industry also declined. In addition, raw material production commenced at many sites in the late 1970s following successful exploration projects.

Depressed prices over a period of nearly 20 years resulted in stagnation of raw material research in the non-raw material producing countries and a systematic decline in German R&D in this field of technology. Increased demand for raw materials since the beginning of the millennium has given initial impetus to capacity expansion at existing sites. However, the remaining reserves are limited at some of the large deposits which are rich in ore that can readily be processed. In order to increase production at those sites, additional resources will have to be invested in extraction and/or processing.

4.1. Mineral raw materials

Industrial minerals and metallic minerals (ore) are classified as mineral raw materials. Technologically, there is a fluid boundary between raw extraction & processing and construction materials technology, the glass industry and the ceramics industry. Industrial minerals and metallic minerals (ore) are extracted from open-pit or underground mines. The interface to the mineral processing stage is located downstream from extraction and conversion to a bulk material suitable for conveying/transportation. Maximum particle sizes in open-pit mining can be 1000 mm or more.

4.1.1. Ore which presents a significant challenge

Readily accessible primary sources of raw materials containing moderately to highly enriched ore which can easily be processed are now largely depleted in Europe. In the case of special metals, few deposits anywhere in the world actually meet all of those criteria. Essentially what remains consists primarily of ore deposits which fail to fully meet one of the criteria mentioned above, or residue (gangue) with low concentrations of value minerals left over from previous processing operations, which now serves as a secondary deposit (tailing dumps). Deposits with low or very low value mineral concentration, complex mineralization or complex composition present some interesting challenges from the process engineering perspective. The list includes: :

» High-quality deposits (higher enrichment) but insufficient size (low accumulation) where extraction has not been economically viable in the past.

» Low-quality deposits (low enrichment) but sufficient size (rel. high accumulation) which can be present as disseminated fine or very fine grained ore (e.g. skarn) that requires very elaborate processing (e.g. comminution to less than 50 µm.

» Deposits containing fine or very fine grained disseminated ore with complex composition (multi-mineral deposits, polymetallic deposits)
  – Deposits where extraction is only economically viable in combination with comminution and sorting at particle sizes < 10 µm or 2 µm
  – Low-enrichment deposits where more effort is required to produce sufficient concentrations
  – Deposits that are only economically viable if more than one value mineral can be extracted

» Deposits with increased concentrations of organic, carbonate or sulfurous by-minerals.

To summarize, there is now a tendency for the raw materials extracted from primary sources to be more finely structured and more complex, and to an increasing extent the value minerals are only present in low to very low concentrations. As a result, fine to very fine grain sizes are increasingly becoming the norm during the mineral processing stage (comminution / flotation particle size).Typical particle sizes necessary to achieve mineral liberation amounts for good deposits in the range of 50-200 µm.

R&D must therefore be directed at the development of reliable process technologies for mechanical liberation of the value minerals and enrichment of the value mineral content by sorting (density sorting, flotation, magnetic separation and electro-separation) and classification down to the 1 (0.5) µm range.

4.1.2. Gaining access to high-tech raw materials

High-tech raw materials have their own specific set of physical properties [23]. Often, these materials are metals which cannot be supplied as bulk metals. In the case of many high-tech raw materials, there are no deposits where these materials are the primary constituent [21]. Instead, many of them are obtained as by-products of the more familiar bulk raw materials (Fe, Ni, Cu, Pb, Zn, Sn, Al, Mg, etc.) (fig. 3). In order to increase production of rare high-tech raw materials, it is necessary to modify the existing bulk raw material production process and extract the target materials from partial, secondary or waste flows. In many instances, changes also have to be made to the production flow for the primary product of the mineral processing or refining stage depending on the structure of the ore. Comminution or sorting is feasible when intermixing exists at the microscopic level. Chemical disassocia-

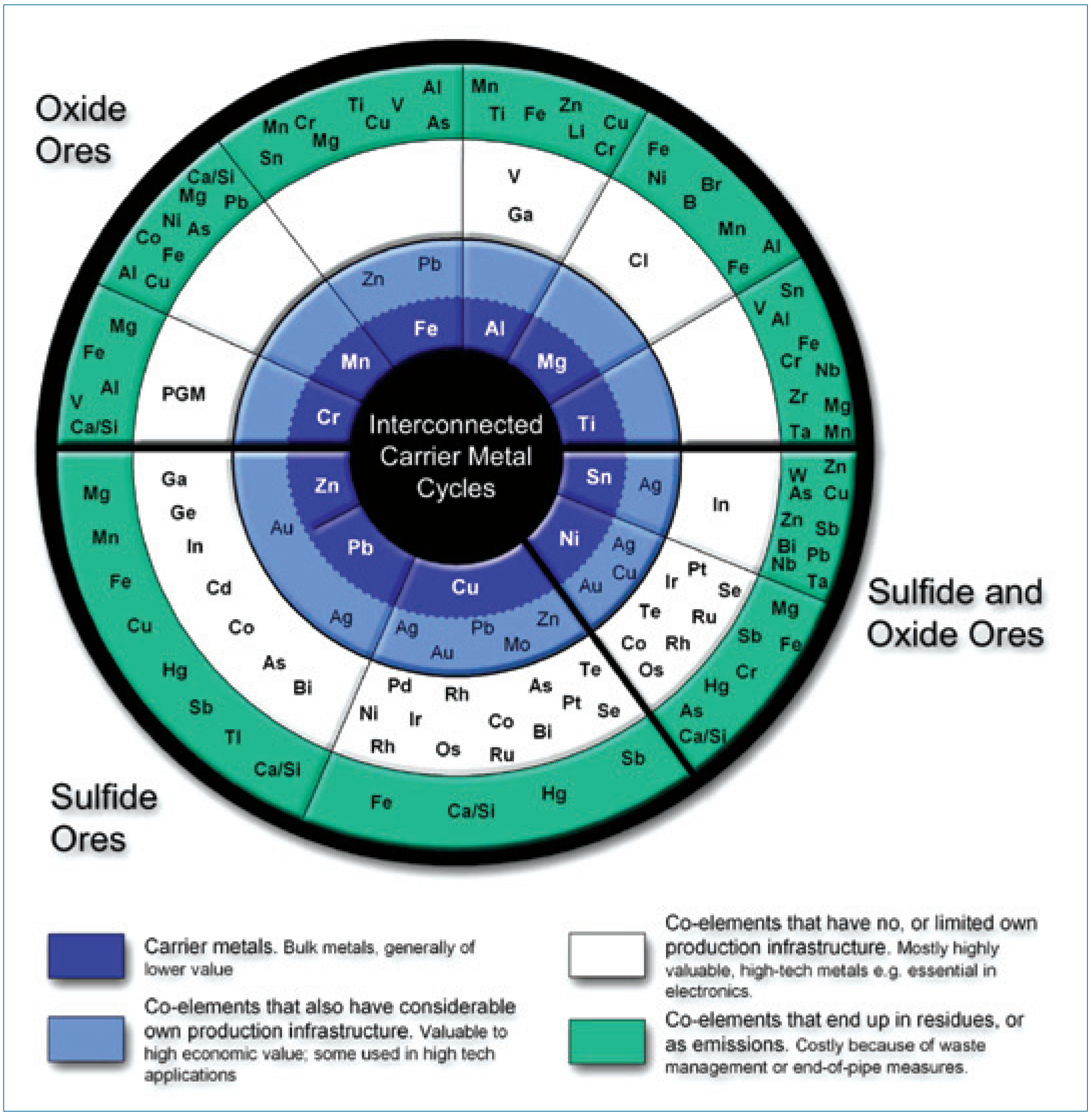

Fig. 3: Interconnection of carrier metal ores with co-elements [4] (metal wheel by Verhoef and Reuter [8])

tion (selective or complete) is needed for intermixing at the atomic level (see fig. 2).

4.1.3. Energy-efficient processing

Comminution, drying and separation account for a significant portion of primary energy consumption in raw material producing countries. The expansion of worldwide production and the need to handle finer particle systems will further increase energy demand. This will affect both the cost and the carbon footprint of the various processes involved. Energy-efficient process designs will have to be developed and introduced to counteract this trend.

4.1.4. Process improvement / process optimization

There are other factors that influence what could become the new European mining model which in principle could be extended worldwide. Zero-footprint mining, which includes the cost of land reclamation, is a political policy objective [4]. One example is the proposed partnership between the EU and the African Union, which contrasts with typical, familiar strategies for managing tailings such as dry stacks and tailing ponds. Mining and mineral processing technologies which meet current standards include

- Emission control (dust, off gas, water, chemicals as well as ore constituents that are susceptible to mobilization)
- Removal of impurities, contaminants and pollutants
- Closed-loop water systems
- Closed-loop chemical systems
- Orderly gangue backfilling
- Reutilization of gangue as a construction material

Enhanced sustainability must be accompanied by an increase in efficiency during the mineral processing phase. New and improved technology can help achieve this goal. Mineral processing automation and management strategies, which create the opportunity to match process parameters with the material parameters of the ore at any given time, offer significant potential [10]. This type of integrated approach is termed geometallurgy [22]. Process simulation (static and dynamic) for solid material processes can provide a good basis for this approach. SolidSim (currently under development) is one example.

4.1.5. Extraction and processing in special situations

Marine mining

Marine mining is a technology of the future. A number of nations including China and India have become heavily involved in this field in recent years. Germany also has exploration fields in the Pacific Ocean. From the technology perspective, offshore gas and oil production is years ahead of marine mining to extract solid raw materials. Autonomous production stations located on the sea floor can now automatically pump the target product to collection points offshore or onshore. In the case of minerals, handling of the extracted ore is more complex. Some of the processing must take place offshore. The following types of deposits are currently under discussion or are at the preliminary investigation phase:

- Manganese nodules
- Crusts
- Shelf crusts
- Metalliferous muds (e.g. Red Sea)

Since these deposits are highly concentrated and located near the surface, excavation, collection, washing and pumping to the surface could be used for offshore extraction (down to sea depths of around 6,000 meters). It can be assumed that most of the mineral processing will take place on land using conventional equipment. Nevertheless, a number of steps will be necessary prior to transportation:

- Concentration (reduction of the sea water content)
- Return of sea water in a sustainable manner
- Optional preliminary sorting, possibly in combination with extraction
- Return of gangue from presorting operations

Sustainability is a major consideration during the return of seawater and possibly gangue as well.

Regions with water scarcity

Wet processing is normally used on primary raw materials if particle sizes are less than around 100 μm. This is the case for liberation (e.g. wet ball mills), sorting to increase the concentration of value minerals (density sorting, flotation, wet magnetic separation), de-watering and sludge removal. Process water is essential for mineral processing. If however the deposits are located in regions where water is scarce, more effort will be needed to supply the process water. Water is a scarce commodity in deserts, semi-deserts, high mountain ranges and regions where the natural water cycles should not be disturbed for envi-

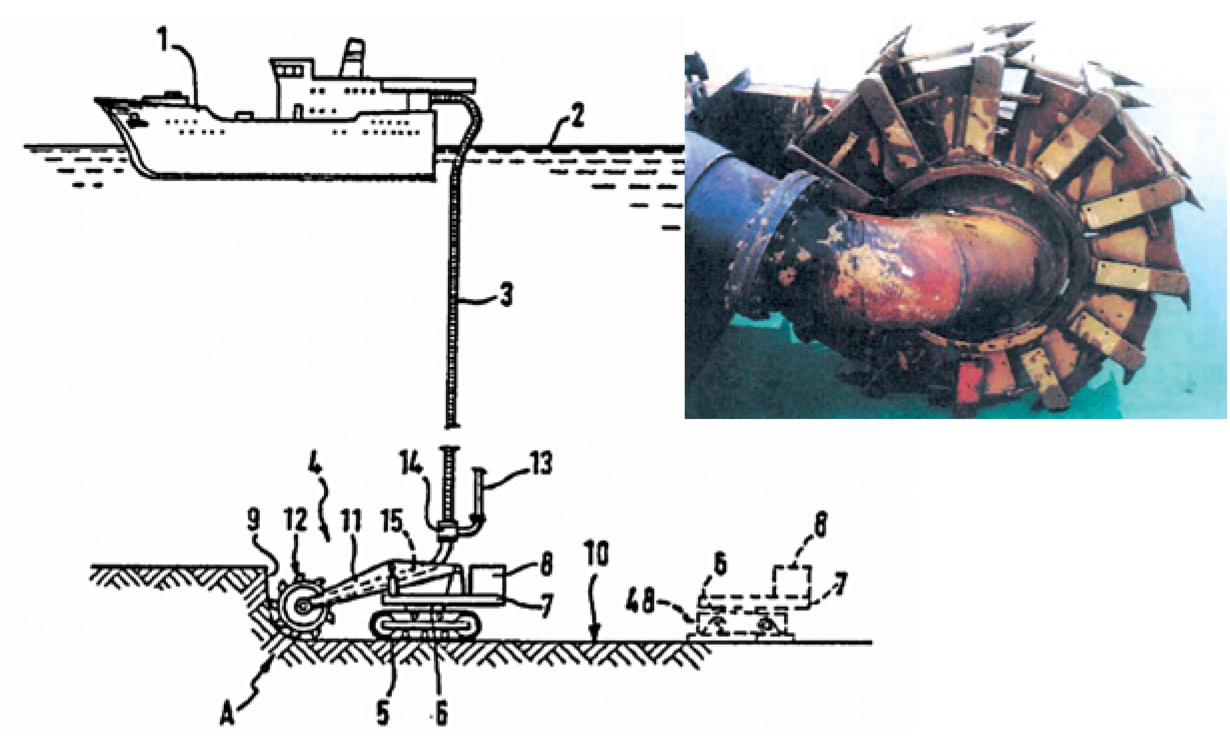

Fig. 4: Technological concept for sub-marine mining equipment (TU Bergakademie Freiberg)

ronmental or sustainability reasons (green mining). Seawater for use in mineral processing is already being supplied by pipeline to some mining sites in Australia.

As a result, there is a need for water-free or water-saving processes and the development of closed-loop water systems. The latter also implies disposal of gangue in the form of dry tailings only, as tailing ponds are the typical drainage sites for process water. Total changeover to dry tailings requires sophisticated moisture removal technology and possibly some method of immobilizing the fine constituents in the gangue as well to prevent wind erosion. A complete closed-loop water system must include water treatment and reconditioning stages to manage pH, chemical content (flotation agents) and salt content.

It appears that a completely closed-loop water system is currently not feasible from the engineering and economic standpoint, because the product and the mechanically dewatered dry tailings always contain a residual amount of water left over from the processing stage.

In particular, dry sorting techniques must be available for water-free processing at sizes below 100 (50) µm. This is the range where particle-particle interaction begins to dominate the process.

4.1.6. The Future Mine concept

The Future Mine concept is presented in the MIFU conceptual study [10]. Northern European mining companies as well as companies and institutions related to the industry are members of the consortium. The MIFU vision is to automate mineral extraction and processing to the maximum extent possible. At underground mining sites, mineral processing will no longer take place above ground. Instead, it will be located underground and linked into the extraction operations. The concomitant advantages are as follows:

- Significant volumes of gangue can be pre-separated
- Material can be backfilled right away
- Improved worker protection and occupational safety
- Reduced space utilization above ground
- Reduced effort and expense for environmental protection, improved sustainability

The extraction process can be automated by replacing drilling and blasting with continuous mechanical excavation (e.g. cutting or shearing). A continuous flow of mineral material is generated at the ore face, and the grain size is smaller due to the method of excavation used. Further processing should take place near the point of excavation using semi-mobile equipment. This includes:

- Conveying ore from the cutting head to the processing stage
- An additional crushing stage with pre-separation of gangue
- The grinding stage
- The dry sorting process (magnetic, electrostatic, possibly density sorting)
- Handling of segregated gangue
- Compact gangue backfilling
- Dust management as a general issue

Since all of these items involve dry processing, they could be designed as semi-mobile and/or compact operations which can be carried out right after extraction. The assumption is that the initial wet processing step will take place above ground or at a central point underground, as water treatment and water management are both essential for the moisture removal process.

Need for further development of mineral raw material processing:

The future of mineral processing will be centered on fine, disperse polymetallic particle systems < 10 µm, and that will require the development of new mineral processing technology. Overall process design must be based on the green mining concept, especially with respect to ecological tailings management. Automation of process management and equipment in the extraction and raw material processing stage will continue to advance, and suitable interactive models will have to be provided.

4.2. Energy resources

A number of strategic programs and landmark political decisions have given energy resources a prominent position on the research policy agenda. Germany is concentrating primarily on sustainable utilization of energy resources.

The scenario which points to a general future scarcity of energy resources on the world market has been a major theme of scientific policy since the oil crisis. Process engineering and processing equipment technology provide the basis for efficient exploitation of energy resources. German companies have a competitive level of expertise in this branch of technology, and that creates export opportunities for both the technology and the equipment. Two particular aspects, which have a certain affinity with the supply of mineral raw materials, are presented below to illustrate that point.

4.2.1. Hydrocarbons from oil sands and tar sands

Oils sands and tar sands differ from conventional hydrocarbon deposits in that the product extracted contains a high proportion of solids (85-90%). These solids need to be separated from the value product (bitumen). Hot water and NaOH or another substance are added to the sand using the Clark-Rowe separation process. Production yields are generally 80% - 90% of the organic content. Highly stable colloidal suspensions are generated as a byproduct from the clay contained in the solids fraction and from the reaction of NaOH with the surfactants which are formed from the organic acids in the bitumen. The suspensions are discharged into tailing ponds. High colloidal stability precludes the deployment of a closed-loop water system, as it takes years for the solids to settle in the pond. Apart from the relatively high energy consumption in the hot water process, the tailings management problem is one of the main challenges during extraction of oil from bituminous sand.

Certain aspects of hydrocarbon production are also related to the extraction of strategic high-tech metals. These metals are contained in noticeable concentrations in the material streams in the petroleum industry (accompanying water, heavy oil residue, etc.), as interfacially-active constituents of the oil or bitumen form complexes with the metals, resulting in enrichment. Efforts are known to be underway, for example, to obtain titanium and vanadium as byproducts of oil sand processing.

Extension of oil sand extraction technology to other types of unconventional crude oil resources such as oil shale and kerogen is conceivable. Some of the material properties, particularly viscosity and solubility, are however considerably different as a result of a different ratio of cross-linking.

4.2.2. Nuclear fuel

Nuclear fuel is a mineral resource. Following the political decision to phase out nuclear power generation in Germany, there appears to be no need for funding at the national level to finance research on extraction and processing of nuclear fuel.

However this field is not a dead end, because materials that could potentially be used as nuclear fuel may be accessory minerals of strategic raw materials. An understanding of these radioactive accessory minerals is needed in order to exploit the strategic raw materials on a sustainable basis. Typical examples include:

- Uranium in phosphorus deposits
- Thorium and uranium in rare earth deposits
- Uranium as an accessory mineral in polymetallic or hydrothermal deposits
- Uranium and thorium in heavy sands

For this reason, expertise derived from radiochemistry and remediation engineering is needed in mining and mineral processing in order to maintain a technological edge and remain a leader in sustainability. This type of expertise is typically required for tailings management. Processing strategies need to be developed which support effective containment of naturally occurring radioactive components (NORM) as well as concentrates which may be generated during mineral processing (TENORM). These tailings strategies go beyond general tailings management and green mining of conventional raw materials.

4.3. Renewable Resources

Renewables which provide a source of energy or raw materials can play an important role in conserving fossil and other non-biogenic resources. Renewables are currently used mainly in the form of biofuel, biogenic solid fuel and biogas to generate energy. The EU Renewable Energy Directive [7] places the sustainable utilization of biomass as a source of renewable energy on the political policy agenda. There is a pressing need for mechanical shredding and classification technologies to process solid biomass such as residue from the forestry and lumber industry. Moist biomass such as agricultural or food processing residue (manure, beet leaves, corn stover, etc.), which is not suitable for combustion, is often used as a substrate in the production of biogenic fuel gas. The production process is generally biotechnology based. Mechanical pre-processing is normally necessary to enhance the available specific surface and process yields.

Biomass could also be an attractive source of renewable raw materials, creating plenty of opportunities for innovative new technologies and products. The list of major renewable raw materials in this field of technology includes vegetable oil and fat, rapeseed, starch, sugar (potatoes, beets and sugar cane), wood, natural fiber, cellulose, rubber, resins, grain (straw) and raw materials of animal origin (implants). The range of renewable raw materials is very diverse. Elaborate, material-specific pre-processing technology will obviously be needed to complement the complex, material-specific production process techniques.

Exploitation of renewable raw materials will provide a path for replacing metal catalysts with enzymes, and biogenic insulation materials can be used in place of oil-based products in the construction industry. In the future, biogenic materials will be used on a broad scale as a renewable source of carbon in the chemical industry, enabling the production of bio-based precursors, fine chemicals and special materials. .

Biogenic raw materials are highly complex and consist of a large number of organic compounds in varying proportions. A large percentage of them are fats, carbohydrates or secondary metabolites. The proportions vary depending on the particular type of biomass. The composition and properties of wood, for example, are much different from those of starch and oil yielding plants. Pre-processing is absolutely essential to make this varied and often non-homogeneous feedstock suitable for a diverse range of high-tech production processes. State-of-the-art raw material pre-processing can significantly enhance process efficiency and product yields.

A series of initial processing steps are needed for renewable raw materials to reduce particle size, increase the specific (reactive) surface and isolate and break down certain fractions, so that the materials are in a state suitable for chemical, physical-chemical and biotech processing.

Lignocellulosic biomass is currently used only as a source of cellulose. No further utilization is made of the other constituents. Wood and straw are some of the main sources of lignocellulosic biomass in Germany. Depending on the type, the wood or straw is composed of around 40 – 50% cellulose, 20 – 30% hemicellulose, 20 – 30% lignin and 2 - 6% other substances. New innovative system solutions will be needed to facilitate industrial exploitation of these constituents. Integrated processing technologies will have to be developed to make quality use of the carbohydrates and also to separate out the aromatic polymers lignin and tannin for downstream utilization. Size reduction is the first step in the processing sequence.

Size reduction increases the reactive surface and induces structural transformation, significantly enhancing raw material efficiency [24]. The size reduction process must be specially designed or modified to accommodate the specific type of wood or straw. Wet or dry size reduction may be suitable. Appropriate classification and sorting processes must be provided for the particles which have highly irregular shapes. New methods for characterizing renewable raw materials are also needed, so that instrumentation can be made available to assess the particles and users are able to effectively manage the process flow on an industrial scale.

Another step in the process flow is separation / isolation of particular constituents using extraction, chromatography and filtration techniques. However in order to significantly expand the product spectrum of constituents in renewables such as lignocellulosic biomass, these steps must be followed by physical-chemical decomposition using pyrolysis or chemical decomposition using ionic fluids, hydrolysis, hydrothermal techniques or supercritical fluids or, to make things even simpler, through techniques such as the Aquasolv and organosolv processes followed by lignin precipitation [1,6,9,15]. Biotechnology pathways for the production of high-value compounds or for the decomposition stage are also conceivable.

For example in the organosolv process, a suspension made up of alcohol, water and lignocellulosic biomass is processed at 150oC – 200oC and around 20 bar. The hemicellulose is broken down into C_5 and C_6 sugars and the lignin is removed from the matrix. Higher levels of mechanical pre-processing prior to chemical processing increase the lignin yield during the process and enhance accessibility for subsequent enzymatic hydrolysis.

Algae contain valuable substances, making them another potentially attractive renewable resource. They contain large amounts of valuable proteins, polyunsaturated fatty acids, oils, natural carotenoids and vitamins. This makes them an attractive renewable resource for the food, cosmetics, pharmaceutical, chemical and bioenergy industries. Algae research is still in its infancy. Algae cultivation is not the only issue to be addressed. Sustainable processing strategies will have to be developed as well.

Further work needed on renewable raw material processing technology:

In general, the transition to renewable resources will necessitate the development of new processing techniques to handle raw materials which have significantly different product characteristics. Existing process designs will have to be modified or adapted to accommodate renewable materials which pose significant process engineering challenges.

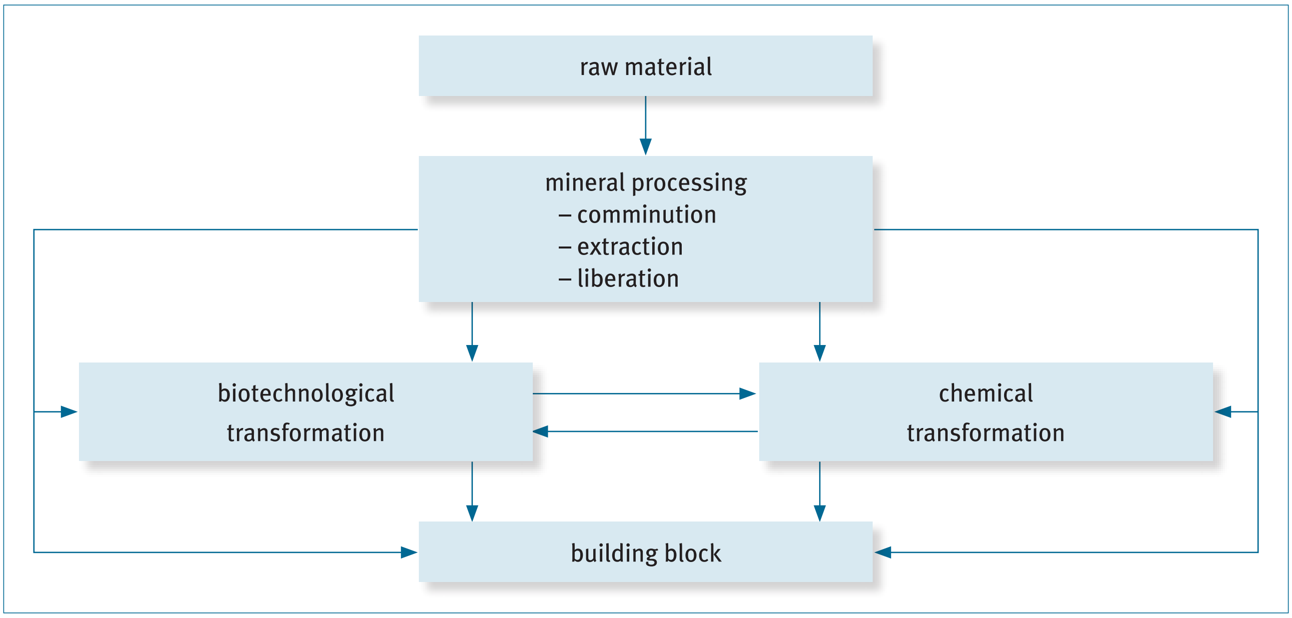

Fig. 5: Typical process chain for renewables

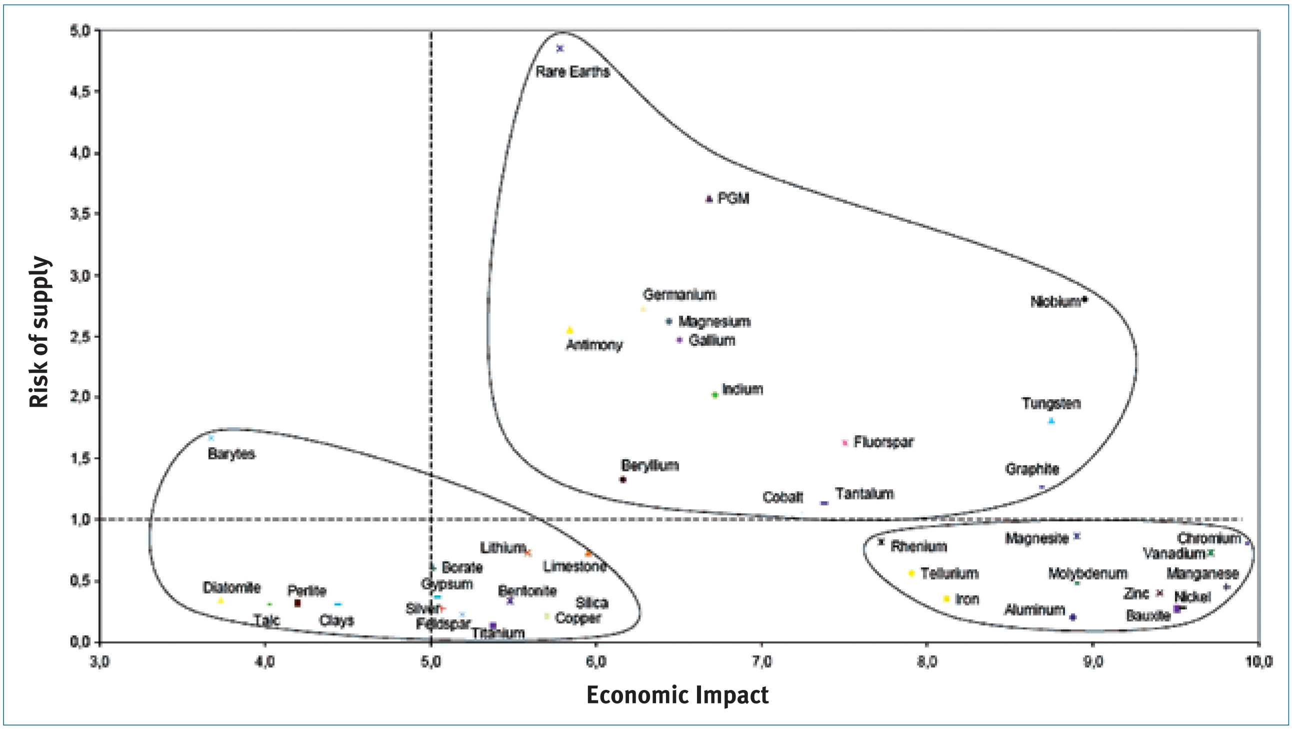

Fig. 6: Visualization of supply risk versus economic relevance of raw materials for the definition of critical raw materials (EU-commission „Raw Materials Supply Group" June 2010, [4])

4.4. Recycling

Recycling, also known as urban mining, involves the return of secondary raw materials to the economic stream. It includes the probing of secondary deposits, extraction of the useful materials and the processing that is needed to produce marketable products. Recycling is able to replace a certain proportion of primary raw materials from secondary sources (recycling rate). Since metals represent relatively high value (material content, commodity market prices), recycling in the iron, steel and non-ferrous metal industries (Al, Cu, Zn etc.) functions relatively well and has the added benefit that it saves energy. Relatively high recycling rates are now being reported for scrap and metal-bearing waste. Because decisions are based primarily on economic considerations, recycling has clearly defined limits in the private economy. Besides ecological constraints (consumption of primary resources unacceptably high) and technical limitations (lack of suitable recovery scenarios, substandard secondary product quality), it is primarily the economic factors (processing costs and cost of waste disposal exceed earnings from secondary products) which restrict recycling. Similar to the situation with primary raw materials, economic viability becomes a problem if

» the concentrations of value materials are high but the volumes are insufficient

» the volumes are high but the concentrations are insufficient

» the composition is complex (bulk and trace metals)

» the material is high intermixed (e.g. composites)

» the material includes impurities and/or contaminants

These difficulties affect not only the actual processing of recycling materials, but also the ancillary activities, namely probing, extraction (including logistics) and residue disposal. Not only that, in contrast to the production of primary raw materials, secondary raw material recyclers are confronted with extremely stringent environmental standards.

Due to protectionist measures introduced by a few (but very important) raw material producers (e.g. China), recycling of strategic rare earth and noble metals and other high-value mineral raw materials has now become a research and development priority (Fig. 6). This type of activity at the national level was not deemed necessary just a few years ago, because sufficient quantities were readily available at low prices. Now that artificial restrictions on the supply side together with an increased demand driven by green technologies (the electromobility initiative, renewable energy, energy conservation) have driven up prices, the break-even point for the recovery of useful materials from secondary sources which are also available in Germany has shifted. Under certain conditions, the recovery of a few high-value and trace elements has now become a more profitable exercise.

In contrast to primary deposits, there are a number of special factors that do not apply to primary raw material extraction and processing which tend to complicate urban mining in Germany:

» The extreme diversity of complex, finely structured composite materials made of bulk metals, rare earth metals and noble metals present in coatings/alloys along with contaminants of largely unknown and constantly changing composition (advances in technology)

» The extreme diversity of particle shapes and sizes

» Extremely wide distribution requiring special collection systems and logistics

» Regional and seasonal factors which affect useful material content levels and composition

» Availability profile (quantity, composition) influenced by objective (e.g. useful life) and subjective (mobile phone hording) factors

» Recycling industry dominated by SMEs → canalization of high-value material flows

» Strong competition for waste categories with high-value content → existing disposal structures, cut-throat competition

» As dictated by the efficiency imperative, the extent of processing performed is limited by the current intrinsic value

» Processing must take place within boundaries set by environmental regulations (emission limits) and customer expectations (stringent quality requirements for recycling products)

These special aspects of secondary raw material recycling (collection, extraction, processing and metallurgy) are likely to be the subject of future research [5].

Hagelüken [3] has depicted the recycling process from collection to metallurgy as a pyramid. The mechanical processing portion is shown with a blue background. SMEs are the dominant force in this segment. The scientific/technological sophistication of the processes used in Germany has reached a relatively high level. However, only a fraction of the existing potential can actually be realized, because the associated material flows are governed by market factors and are not representative, not constant over time and by nature not easy to generalize. The material flows are a function of industrial production and investment cycles as well as consumer behavior, and a time shift factor is also involved. As a result, time to market is critical because recycling solutions are only viable over a limited time window and they must be continuously improved and updated.

Recycling of macroscopic structures > approx. 1-10 mm is highly advanced in Germany. Automation and selectivity have increased substantially with the introduction of sensor-based processing. A lot of development work remains to be done on fine and ultrafine composite materials.

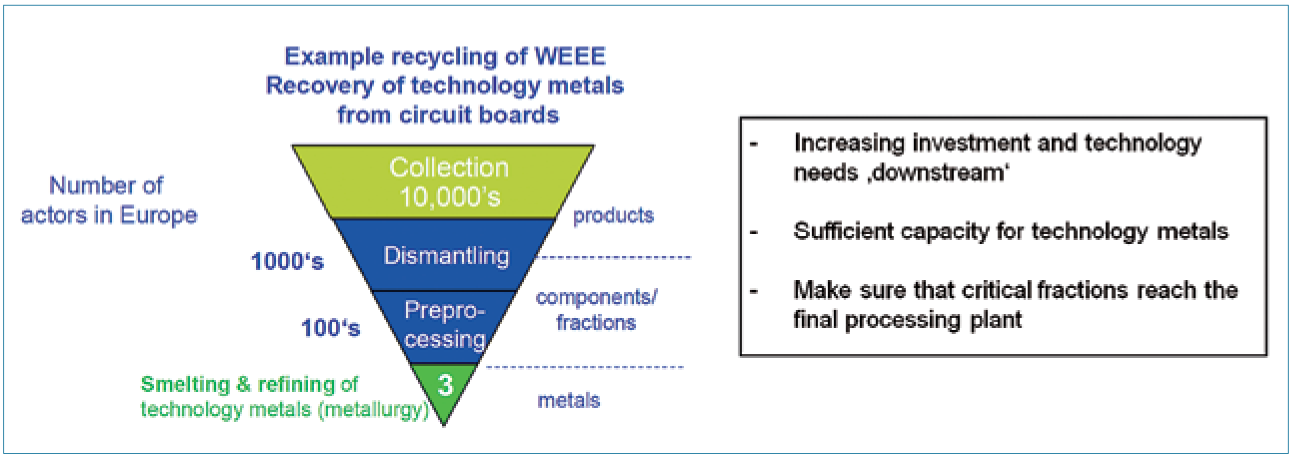

Fig. 7: Organization of the recycling business after Hagelüken [3]

Noble metal coatings in the electronics industry applied using CVD or electrolytic techniques have thicknesses in the single-digit micrometer range. Detecting, exposing and removing these components from the complex electrical and electronic scrap generated by the information age are very demanding tasks indeed. Electronic components such as printed circuit boards, cell phones, automotive electronics and laptop computers are in many ways comparable to highly complex polymetallic ore containing high concentrations of metal. Most of these metals can be recovered using metallurgical techniques alone, but energy consumption in this type of thermal processing is disproportionally high. As energy prices continue to rise, mitigation of the problem is not to be expected any time soon. Managed enrichment based on selective collection of goods that have similar composition accompanied by specially modified comminution and sorting techniques is a much more promising approach. Product quality and recoverable material yields can be enhanced by closely matching the different material processing stages to the specific goods being handled, and this strategy also reduces the amount of effort involved in downstream metallurgical processing.

Need for further work on secondary raw material processing:

Mechanical recycling (sorting and comminution) must advance into the length range (> 1 µm) which is characteristic of current high-tech equipment. Collection logistics determine the expected processing plant size.

5. Contribution from process engineering

At the international level, many current and future coordinated solicitations for research proposals in the field of mineral processing can be expected to specifically require a demonstrator to be used for pilot testing of new innovative technology and equipment. Apart from transfer technologies, Germany at least in the academic sector has some catching up to do in terms of R&D. Using the current state of raw materials technology and policy as the starting point, basic engineering R&D will have to be directed at the development of new technologies which can then be expanded as needed during the applications engineering phase.

Definition of the innovation space will be derived from the list of issues outlined above. In terms of basic specification, it appears that there will be a need to produce fine and ultrafine particle systems from the various ores, secondary raw materials and renewables. This stage will be followed by sorting and concentration. By-products and impurities will have to be removed and their handling characteristics will have to be adjusted. In the case of ore and secondary raw materials, there are fluid, overlapping boundaries at the interfaces with extraction and metallurgy. The same applies to biotech or chemical transformation of renewable raw materials.

All of the typical factors which play a role in mineral processing technology apply to ore processing:

» Large volume flows
» Resilient processes that lend themselves to automation
» Not all of the material properties are detectable with sensors
» The different deposits have varying, unique characteristics (problem in defining model products)
» Existence of unused material streams and sustainable disposal of those streams (tailings)

Typical factors related to renewable and secondary raw materials:

» Small to medium volume flows of varying origin (problem of material consolidation, to some extent over large distances, based on maximized logistics intelligence)
» Secondary raw materials contain a highly heterogeneous material mix; renewable materials have high biovariability

5.1. Mechanical Process Technology: Comminution / Classification

Comminution and classification (i.e. separation based on particle size) play a major role during the processing of primary, secondary and renewable raw materials, because these operations take place at the beginning of the processing sequence and have a big impact on the efficiency

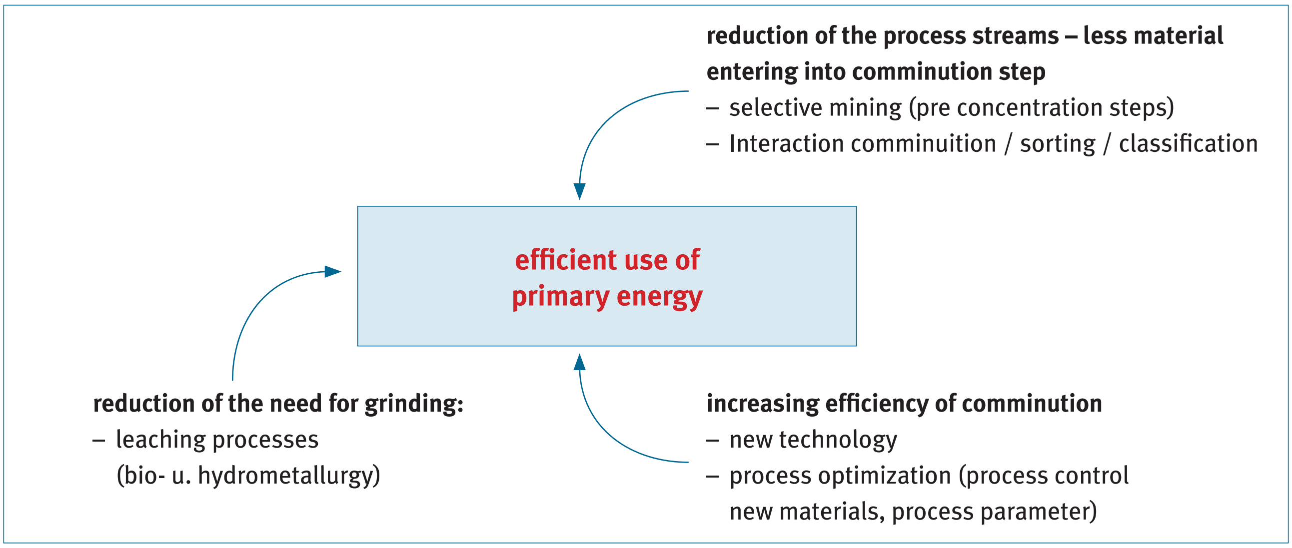

Fig. 8: Strategies to improve energy efficiency in comminution processes (schematic after MIFU Report 11/2010 [10])

of the downstream processing stages. Comminution is also one of the main points of primary energy consumption in the material processing flow. The high material throughput volumes in ore beneficiation illustrate this aspect very clearly. There is a definite need to increase energy efficiency, and a variety of strategies have been outlined (fig 8) The list includes alternative processing techniques (change of principle), a reduction in material processing volumes and increased energy efficiency in the actual grinding process (process intensification). Similar approaches will be needed for secondary and renewable raw materials. In particular, new and more effective comminution techniques will have to be developed for ultrafine size reduction of renewable organic raw materials.

List of process engineering tasks for comminution and classification

» R&D on energy-efficient comminution at high throughput rates and high fineness grades (down to around 1 µm)
  - basic and applied research on crushing and ultrafine grinding (< 100 µm) of
    - heterogeneous particles structures (e.g. ore, secondary materials)
    - non-brittle organic materials
    - multi-material systems (e.g. hard and soft)
    - fibrous materials
  - pre-processing (e.g. thermal or chemical) to influence crushing characteristics
  - model-based description of crushing and comminution behavior for complex materials (multi-component population balance)
  - new comminution and classification technology, new grinding and classification techniques with enhanced energy efficiency based on factors such as
    - the use of integrated instrumentation to achieve a better understanding of what exactly takes place inside a grinder
    - a reduction in the number of comminution steps
    - increased use of wet grinding during material processing
    - new combined grinding/classification techniques, in particular to achieve narrower particle size distributions
  - an understanding of the dynamics involved in grinder/sifter loops and, building on that knowledge, development of new control strategies for the interaction between comminution and classification
  - reduction of waste streams by managing the way in which the material is stressed (including avoidance of ultrafine particles during dry processing)
  - integration of additional processes such as leaching, extraction or reactions with comminution in grinders
  - prediction of material adhesion in grinders and classifiers and avoidance strategies
  - deployment of grinding aids to alter the grinding limit and reduce the formation of deposits
  - in-depth understanding / minimization of grinding machine wear

» Development of effective classification techniques as a sorting method
  - simulation of particle motion in complex, highly-laden gas and liquid streams (dense multiphase flow)
  - development of new classification techniques for
    - fibrous particles
    - particles < 10 µm
    - highly selective sorting with narrow particle distribution
    - selective discharge of enriched particulate fractions from processing loops
  - combined comminution / classification used as a sorting process

» Basic understanding and process expertise in selective size reduction and comminution of complex technical structures (composites) and renewable raw materials:
  - metal-metal composites (hybrid parts)
  - polymer-metal composites [14]
  - polymer-fiber composites (MRP, NRP, GRP, CRP)
  - biomaterials (e.g. wood)
  - technical coating structures (CVD layers, coatings, electrodes)

Comminution / classification: additional research needed

Comminution:
- influence material properties – shorten mechanical processing sequences
- energy-efficient use of wet grinding
- ultra-fine comminution of non-brittle and fibrous materials
- selective comminution of heterogeneous materials (esp. composites)

Classification:
- classification of ultrafine particles and fibers
- new configurations and control strategies for grinder/classifier loops

5.2. Mechanical Process Technology: Sorting

Sorting is a key step in the mineral processing sequence. The gangue needs to be separated from the ore. Yield, purity and value mineral content are the standard quality parameters in the sorting process. Additional secondary quality characteristics can also be defined. The concentration of certain impurities has particular importance. In general, sorting can only take place if the particles are mobile in relation to each other, which means that they cannot be bound in ore composite or agglomerates. The choice of sorting technique depends on the sorting criteria. Dry sorting, magnetic separation, electrostatic sorting and density sorting reach their technical limits at around 50-100 µm, because that is where van der Waal forces begin to create heterogeneous agglomerates.

Wet sorting is used for fine grain sizes and to increase selectivity if the magnetic / charge properties or the densities of the mineral constituents are not sufficiently differentiated. This can take the form of density sorting, magnetic separation or flotation.

Due to the higher level of material breakdown (i.e. creation of finer particle systems), there is a need for

» sorting techniques for ultrafine particle systems with very fine grains (< 50 µm, mainly in the 0.1 µm – 10 µm range)

» classification to assist the sorting process – sorting in narrow grain size fractions

» strategies for handling raw materials with very high levels of impurities (clay, organic constituents, radioactive substances)

For dry sorting:

» expansion of sensor-based sorting technologies [2] (size range, applications)

» sorting of heterogeneous material streams (recycling)

» continued applications engineering development to increase gradients, improve transport and influence particle adhesion in dry magnetic and electrostatic sorting

For wet sorting and flotation in particular:

» hydrodynamics management in large flotation systems – increase bubble-particle attachment probability

» dissolved air flotation at different pressure levels

» equipment designs which segregate bubble generation from the bubble-particle contact zone

» systematic investigation of the interfaces involved (see section on interfacial process engineering)

Further research needed on sorting:

» Particle systems < 10 µm – management of particle-particle interactions

» Influencing separation characteristics to increase selectivity [25]

» Expansion of the applications range for sorting techniques

5.3. Mechanical Process Technology: Mechanical Separation

Finer breakdown creates the need to handle fine dust and suspensions. While state-of-the-art techniques are currently available for gas purification, there is significant need for effective fluid separation technology:

» handling of fine and ultrafine concentrate and gangue suspensions

» strategies and process solutions for dry tailings, i.e. generation of solids for safe disposal from the tailings suspensions [19]

» processing techniques for highly bimodal solids systems (e.g. clay content in the raw material)

» systematic studies on de-sliming and purification

» cleaning to remove auxiliary substances from the gangue and value mineral fraction (dehydration/ washing)

» filter cake washing to increase leaching yields

» water management / recovery of mining chemicals

» systematic investigation of the interfaces involved (see section on interfacial process engineering)

» mechanical separation at increased pressure and temperature

Further research needed on separation technology:

Washing:
– reduction in organic and dissolved ionic content in gangue material streams (secondary applications)
– better yields (hydrometallurgy)

Dehydration
– management of handling characteristics – suitability for dumping, high fines content / – bimodal particle size distribution (clay minerals)

5.4. Bioprocess engineering

Biological processes are by no means unknown in mineral processing, and they are used where suitable. The main example is biological leaching which is used to a large extent in copper production. There are also initial applications for nickel and uranium. The term geo-bioprocess engineering has been coined to describe this field of technology, and it includes the following:

» bioleaching (technology already introduced for Cu)
  – extension to other high-value metals
  – basic studies
  – process modeling and optimization
  – integration into conventional process steps (handling of process water, extraction, tailings, etc.)

» biological effluent treatment (sulfates, etc.)

» biomineralization
  – use of microorganisms to convert dissolved substances into a high-purity solid

» use of materials and substances synthesized with biotechnology
  – selective adsorbents made of S-layer proteins
  – biosurfactants [26]
  – complexing agents

» biotech transformation of renewable raw materials

Further research needed on bioprocess technology:

Bioleaching:
– selective mobilization of metal ions for low-concentration co-elements
– extension of the bioleaching applications horizon to other main elements

Biomaterials:
– surfactants, extractants, flocculants made from renewable resources

5.5. Interfacial process engineering

Flotation separation is the main sorting technique used in mineral processing. Sorting is based on the different adsorption characteristics and resulting wetting characteristics on the surface of the raw material particles. Three-phase contact (gas bubble – aqueous suspension fluid – solid) is an essential aspect of the process. Interfacially active substances are added and the pH value and ionic strength are adjusted to modify the surface and interfacial properties of the solid. Collectors reduce wettability while depressants increase it. Frothers ensure that a stable foam forms at the top of the suspension for removal of the solids. It is not currently possible to fully describe the interaction between a complex mineral interface and an interfacially active substance (surfactant, polyelectrolyte, polymer, complexing agent, etc.). Development of flotation reagents which produce specific effects involves the molecular design of active molecules. Basic development work is needed in the following areas:

- theoretical prediction of interaction between flotation chemicals and mineral interfaces, or molecular modeling
- development of selective flotation chemicals for oxide ore

Technological advances in the chemical industry (modification of the production process, cessation of production and aspects related to REACH certification) along with more responsible use of process chemicals have restricted the availability of various bulk chemicals which are

Fig. 9: flotation cell in mineral processing (Clariant)

used as flotation agents. The transformation of chemical production has made it necessary to find new sources and new types of mining chemicals. This means that:

- new mining chemicals (flotation agents, flocculants and extraction agents) which are compatible with sustainability standards will have to be developed and/or made available.
- there is a need to determine whether partial flows used in industrial biotechnology are suitable for flotation applications, e.g. biodiesel (polyglucans, oligosaccharides and polysaccharides)
- recovery and circulation loops for flotation reagents
- cleaning to remove flotation reagents from the solid (minimization of the organic burden)

Based on experience from mining applications, deployment of flotation to sort ultrafine particles in secondary and renewable raw material processing needs to be developed and studied.

Further research needed on interfacial process engineering:

- Basic principles for selection and design of mining reagents
- Interaction of mineral structures with functional organic groups
- Ways of influencing the interfacial energy of minerals

5.6. Extraction and chromatography

Apart from mechanical processing technology, there are other options with innovation potential including:

- ion exchange
- functional surfaces and membrane adsorbers
- extraction using organic phases
- affinity chromatography

German chemical companies are at the leading edge of technology in this field and have a presence in the world market. To provide innovative, integrated process solutions, enrichment based on extraction, leaching and ion exchange must be viewed in combination with the primary mechanical processing operations.

Affinity techniques will play a bigger role in the future in mineral processing at polymetallic deposits where no single main metal is present in concentrations that are at least an order of magnitude higher than the rest. Following leaching, multiple metals will have to be selectively extracted from a polyionic solution. Besides crystallization and electrolysis, extraction can take place in a liquid-liquid or a liquid-solid process. In both cases, separation is based on selective ion complexation by amphiphilic organic molecules. The technological challenges are as follows:

- development of chromatography materials for selective separation of metal ions
- development of high specific surface nano composites for use as selective adsorbents
- operation of chromatography columns for selective separation of ions from hydrometallurgical solutions
- process management and design of adsorptive separation strategies for polyionic solutions
- evaluate the suitability of alternative adsorption processes and expanded bed adsorption for processing with solid-bearing solutions which are used in hydrometallurgy

5.7. Alternatives and hybrid processes

Looking beyond the realm of the standard basic mechanical processing operations, there are a number of hybrid techniques, some of which already have a proven track record in chemical mass production, that may provide a pathway to a quantum change in approach, including:

- hybrid / integrated processes
  - steam pressure filtration
  - reaction grinding
  - selective magnet separation
- processes with supercritical media
- high pressure processes
- plasma and high-voltage processes

5.8. Raw Material Processing

Raw material processing typically involves large mass flows and relatively high cost and effort. In absolute terms, small fluctuations or improvements in quality levels can significantly improve performance (efficiency, reduced CO_2 emissions). From the process engineering perspective, raw material processing is a highly interconnected sequence of operations where the various steps, each having its own process function, interact. In order to describe and quantify these interactions and use them for process intensification, it is necessary to create a complete process model based on an increased number of parameters. Well-designed flow sheet simulation (stationary and dynamic) as well as enhanced acquisition of particle parametric data and use of that data for control system design could generate process engineering value-add. The following issues should be at the top of the priority list for development of the intelligent mine and raw material processing optimization:

- simulation to gain an understanding of the process (flow sheet simulation for solids)
- measurement systems for acquisition of characteristic process parameters
- structure-characteristic function: extended parameter set, e.g. geological, geotechnical, crystallography parameters, as key process parameters
- near-to-face mineral processing, e.g. extraction followed directly by backfilling
- process design using semi-mobile extraction and processing equipment at open-pit mines

6. Summary

In terms of the educational framework and the technology, mineral processing has provided the foundation from which process engineering has evolved over the past 100 years or so. Structural change in Germany starting in the 1960s has reduced the economic importance of mineral processing. To an increasing extent, advances in process technology are being rolled out in other industries including (bulk) chemical production, recycling, environmental technology and biotechnology. There is still a high level of process engineering expertise in Germany coving a wide range of material streams. Knowledge can be transferred from the many other fields of process technology research in order to strengthen and drive forward research in raw material processing. However, a detailed understanding of ores, minerals and crystal structures will have to come from the geo sciences. A synthesis of process engineering knowledge with an understanding of materials based on geo science could well be a successful strategy for enhancing German raw material extraction expertise. The available capacity for raw material processing research and mechanical processing research could provide the link between process technology and the geo sciences.

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