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# Energy Consumption in Mining Comminution

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**Abstract**

The supply chain for metals used in manufacturing is usually from premanufacture (mining). Energy impact needs to be considered, with it being one of the five stressors that impact the environment. In this paper the energy needs for crushing and milling (comminution) are presented. A brief comparison is made with the energy needs for recycling of large scale waste products such as automobiles. A simple method for product designers, which uses Streamlined Life Cycle Analysis, is proposed for assessment of mining value chain impacts.


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*Keywords:*
Energy; Mining; Crushing; Comminution

## 1. Introduction

This paper is about energy consumption by comminution in mining and assessing its environmental impacts with an SLCA, Streamlined Life Cycle Analysis. The intention is to provide designers with a brief review of comminution, the energy used, and how to use SLCA to assess its impacts. Product designers do not have this information immediately available and this paper intends to meet that need.

In SLCA, premanufacture is a euphemism used to describe the life cycle stage, stage 1, prior to manufacture, stage 2. Mining will be used in this paper, with the understanding that it is premanufacture stage 1.

When dealing with environmental concerns, it is useful to revisit the four anthropocentric, environmental "Grand Objectives": 1) Human species extinction, 2) Sustainable development, 3) Biodiversity, 4) Aesthetic richness [1, 2].

Specific details about each of these, *with material supply chain concerns italicized*, are: 1) *Minimize environmental toxicity*, provide basic needs, food, water, shelter; 2) Energy supply (sustainable), *availability of material resources and recyclability*, political stability; 3) *Maintain natural areas*, maximize biological diversity (ie: avoid monocultural vegetation); 4) *Control of wastes, minimize emissions, minimize dumping, minimize degradation of physical geography,* avoid land overuse. This list was made up in 2001 [1, 2] has withstood the test of time and is still applicable.

### 1.1 Assessing Environmental Impacts

The most detailed way of assessing environmental impacts is by doing a complete Life Cycle Assessment (LCA) [3, 4, 5, 6]. If done properly, an LCA will consume years to complete. Norgate et al [6] consider gross energy requirements for mining specific metals, but do not look at a method for looking at a specific mine energy requirements. An SLCA, Streamlined Life Cycle Assessment [2], is recognized as a reasonable method of assessing impacts, having a shorter time span for completion. SLCA will be used in this paper. SLCA does not appear to have been used specifically for mining before.

The five Life Cycle stages [2] are *Premanufacture (mining or recycling), Manufacture, Transportation, Use, and End-of-Life*. For this paper, *premanufacture (mining)* is the stage of concern. The environmental stressors are: *Materials, Energy, Solids, Liquids and Gases*. For this paper *energy* is of concern. Combining the stages and stressors gives a 25 cell matrix, with cells 1,1 to 1,5 being those of concern to mining. There are five 25 cell Environmental Responsible (ER) matrices: product (ERP), process (ERP), facility (ERF), service (ERS) and infrastructure


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(ERI). Weightings can applied to each matrix cell and also to each RR matrix. Each matrix cell is given a rating from 0 (poor) to 4 (very good), where 100 is an excellent score for a matrix. For example for a Facility (ERF) matrix, at the mining stage, with *energy as a stressor*, cell 1,2, the choices for assessment are [2]:

- Rate 0, for a complete new energy infrastructure installation;
- Rate 4, for non-modified, existing energy infrastructure. This assumes the existing energy infrastructure is at the lowest impact, most efficient level;

An assigned rating of 1, 2, 3, depends upon the degree to which the infrastructure meets *design for environment* preferences.

- The energy infrastructure site avoids emission impacts upon surrounding biota, rate 3;
- The energy infrastructure can be made operational with minimal energy expenditure, rate 2;
- The energy infrastructure enables delivery and installation of construction with minimal energy use, rate 1.

More examples are given in section 6.

Material use is also of concern, but is not discussed here. However, the designer must be cognizant of potential resource scarcity of metals such as lithium, indium and rare earths. Graedel [7] states: "determining criticality is a complex and sometimes contentious challenge". What is missing in the discussion on material criticality, is an understanding of mining with respect to all three pillars of sustainability.

To be able to assess mining impacts basic knowledge if the process is needed, hence the following information about mining is included.

## 2. Mining

Mining is the first link in the supply chain for metals in manufacturing. Material in the supply chain is either from recycled material or mining, with *100% recycled material being the ideal optimum* (called a circular economy) thereby circumventing mining and reducing environmental impacts. However, it will be a long time before we live in a circular economy (total recycling), so we must ensure minimum impacts due to mining. Ultimately mining is concerned with: Percent metal present in the ore; Refining, or removing impurities or unwanted elements; Slag, waste matter separated from metals during smelting or refining; Flux, inorganic material that separates metal from unwanted material.

The flow charts for base metals in the mining supply chain and the value chain for raw materials are both shown schematically in figure 1 [8, 9]. Metal concentration, specifically processing and refining, comes immediately after the extraction process as shown in figure 1.

In the mined material supply chain, ore concentration is the process whereby the mineral being mined is separated from mineral bearing rock, either chemically or physically. Prior to this the ore must be crushed to a size suitable for grinding. Grinding is then done to produce fine particles which can be processed either chemically or physically.

Although this paper *concentrates on energy consumed in comminution (particle size reduction: crushing and grinding)*, the minimization of environmental toxicity or maintaining of natural resources is also directly and indirectly linked with the material supply chain, but is not discussed in this paper.

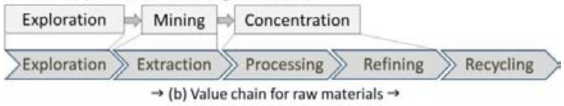


Figure 1. Flow charts and value chain for raw materials [8, 9].

### 2.1 Energy Consumption in Open Pit/ Underground Mines

There is a dearth of information about energy consumption specific to individual mines. One study [6], which is a collaboration that compares seven mine mill/concentrator operations: four gold and three iron ore mines. The average energy needed for seven mines is summarized in figure 2, where the energy requirement is broken down into six components: crushing, grinding, processing, tailings, process water, plant general (ancillary). Adding this energy to the average energy needed for an *open pit* mine, calculated as 11,766 kWh/kilotonne in [6], or the average energy needed for an *underground* mine, 10,241 kWh /kilotonne [4], the energy needs for an open pit with refining, will be ≈33,507 kWh/kilotonne [5].

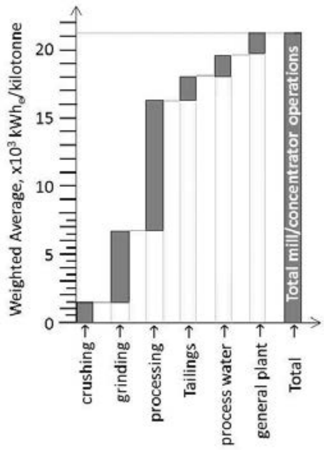


Figure 2. Average energy needs for mill/concentration operations [8].

Energy requirements for both open pit and underground mines include electricity and a variety of carbon fuels: natural gas, propane gas and diesel fuel [9]. Both open pit and underground operations are very different and have different energy needs, for instance, underground mines have HVAC energy needs, whereas open pit mines do not. Both mine types need pumps for water flowing in from the water table with pumps accounting for approximately 25% to 32% of total motor energy consumption on an average mine site. Globally it is estimated that all pumps consume 15% of available electricity. In addition, HVAC energy requirements can be at least 25% of underground mine energy needs [10].

Mining energy consumption contributes to mining operational costs and occurs at all stages of the ore recovery process: blasting, excavation, crushing, transport and grinding (comminution). For example, the copper mining industry is expected to consume 41.1 terawatt-hours (TWh) in 2025, an increase of 95.5 percent from 2013 [11]. New mining projects alone are predicted to consume 36.2 percent by 2025. The world's biggest copper companies use concentration plants, which are energy intensive and use the world's biggest pumps in their main production process. The distribution of energy at a mine site is 3 – 5% for blasting, 5 – 7% for crushing, and 80 - 90 % for grinding [10, 11].

Energy consumption occurs everywhere in the mining and manufacturing sectors. For relevance in energy consumption, table 1 compares energy consumption for certain parts of the mining sector with other global energy consumption.

Table 1. Examples of mining energy consumption, global and specific.

| Energy Consumption | % |
|---|---|
| *Global comminution* electrical energy consumption | ≈4 |
| *HVAC* total global energy consumption | 12 |
| *Single mine* HVAC energy consumption | 25 |
| *Pump global* consumption of world's electricity | 15 |
| Max efficiency pump use reduces global energy consumption | 7 |
| Europe total electricity consumption to produce *compressed air* | 3 |
| Total *pump motor energy* consumption on an average mine site | 25-32 |

## 3. Comminution and Mill Energy Requirements

Comminution includes both crushing and grinding. Initially, ore is reduced in size by crushing rock to a size that makes it manageable. Crushing is accomplished by compression of the ore against rigid surfaces, or by impact against surfaces in a constrained motion path. Crushing is usually a dry process, and is performed in several stages, reduction ratios being small, ranging from three to six in each stage. The reduction ratio of a crushing stage can be defined as the ratio of maximum particle size entering to maximum particle size leaving the crusher, although other definitions are sometimes used. There are a number of crushers available such as jaw, gyratory, cone, roll, and impact crushers [12].

Crushers are often located in underground mines where they reduce the size of rock, in situ, to a more manageable size for transport. Crushers are available in all types of configurations. Two types are illustrated in figure 3. Once crushed, the material is then skipped (conveyed) to the surface, and usually hauled short distances by conveyor to an area where it is ground. When trains are used to transfer rock, it will be for kilometers to the metallurgical site. A train may use twenty-five to thirty 90-tonne rail cars and make 4 to 5 trips per day.

Crushers are the first stage of ore processing. Depending upon the application, power can range from 180 kW (240 HP) to 1200 kW (1600 HP). Rocks as large as 50 cm in diameter are reduced to 15 cm fragments [11, 13] which are then reduced to fine particles in SAG (Semi-Autogenous Grinding) or Ball mills. Crusher utilization average is 65% which is similar to equipment utilization in many manufacturing industries.

An example of rock processing is in the Sudbury basin, where 141,981,254 tonnes of waste rock was produced by 16 mines over 100 years, with nickel, gold, platinum and silver being mined. It is estimated that over US$120 billion worth of nickel, copper and platinum group metals (PGM) have been produced from the region [14].

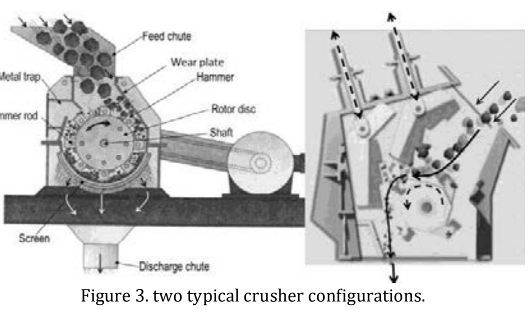


Figure 3. two typical crusher configurations.

After transfer, the ore is processed. Both open pit and underground mines have processing (milling) and refining facilities which are usually located onsite and are major energy consumers. In 2013, concentration plants represented 48.6 percent of the total global energy consumption for the copper mining industry. This is expected to increase to 64.2 percent by 2025, reaching 26.4 TWh [13].

### 3.1 Grinding

The purpose of milling (grinding) is to reduce the ore to a desired particle size, which can be processed chemically or physically, extracting the mineral sought from the ore often by electrochemical means – concentration.

Energy efficiency is low in grinding processes where most of the energy is dissipated as heat in the rock. Additionally, there is high variability between mine ore hardness and size distribution in feeding the grinding process, giving different inefficiencies. Ore is sometimes segregated in muck piles (piles of ore) and silos where the ore it is collected before being transferred to the grinding process

Refined product throughput is decided by the power available. Energy consumption is described by kWh/tonne with mill efficiency is described by kW/m$^3$ and material throughput described as t/h (tones/hour).

Whereas crushing is usually a dry process, grinding is usually performed wet to provide a slurry (liquid) feed to the chemical concentration process [15].

With rock reduced to a manageable size by crushing, grinding mills then reduce the rock even more to a particle size that makes chemical processing viable. Comminution is the process in which the particle size of ore is progressively reduced until particles of mineral have been separated. Comminution (grinding) consumes up to 4% electrical energy globally [15, 16, 17] and about 50% of mine site energy consumption is in comminution. For a single mine, average comminution energy consumption can be approximately 6,700 kWh /kiloton.

Grinding is accomplished by abrasion and impact of the ore with moving media such as rods (rod mills), balls (ball mills), or pebbles (sized ore in AG & SAG mills). These vary in size according the size of particle being processed. The grinding media is mixed in with the ore as it is processed. or

The grinding media used depends upon particle size desired and energy considerations. As particle size decreases, grinding media size also has to decrease for efficient grinding to take place. As grinding media size decreases, its velocity has to increase in order to generate sufficient energy for particle breakage. Mill efficiency, kW/m$^3$, is dictated by the type and size of media used.

Grinding mills are usually the highest cost items at a mine site and have a variety of configurations: Ball mill, rod mill, HPGR mill (high pressure grinding roll), SAG (Semi-Autogenous Grinding) mills and stirred mills. SAG mills, see figure 4, are characterized by their large diameter and short depth, and are primarily used in gold, copper, molybdenum and platinum mines with additional applications in the lead, zinc, silver, alumina and nickel mines.

SAG mills can be as large as 8.5 m in diameter with a 22 MW motor. One of the largest SAG mills (12m diameter), has a variable speed GMD (gearless mill drive, made by ABB) drive and has a capability of 28 MW for refining copper-molybdenum-silver [13]. Mills usually have motors in the following range: SAG mill motor: 7,435 kW or an HPGR circuit with motors: Ball mill 1 (4,015 kW) and Ball mill 2 (4,152 kW) for a porphyry copper-molybdenum mine.

Comparing mill operations for both open pit mining to underground mining, where the metal is separated from rock ore containing the metal mined, both open pit and underground mining have the same energy needs, in kWh/tonne.

Although SAG mills and Ball mills are commonly used to decrease the size of ore bearing rock, the mining industry is driven to decrease costs, as are all industries. This means increasing comminution efficiency and decreasing energy costs. Stirred mills [17] have been found to be 50% more efficient than Ball mills. There are 12 different types of stirred mills, one being the ISAmill [18] shown in figure 5.

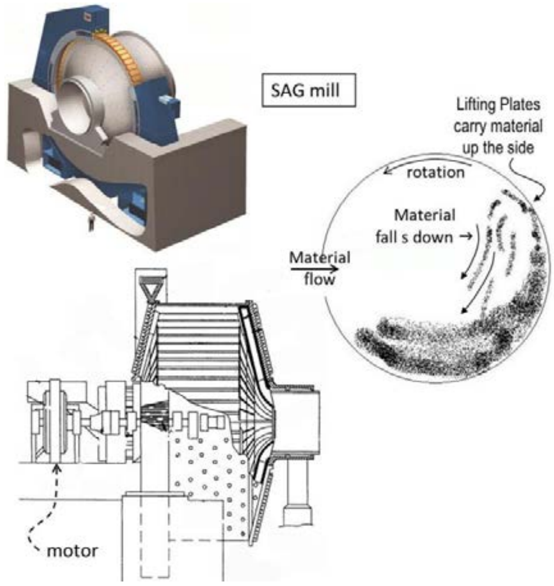


Figure 4. Illustration of a SAG mill. Most mills are much smaller.

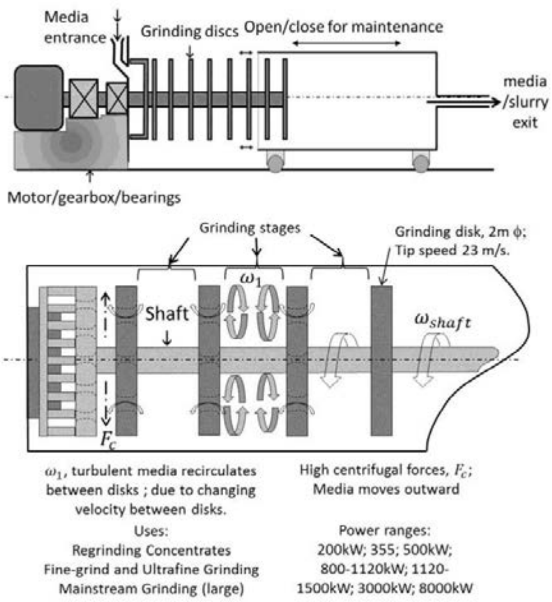


Figure 5. Illustration of an ISAmill [18].

## 4. Recycling Energy Use Similarity

A brief comparison to energy consumption of large size objects in recycling is made here to place mining energy consumption in context. In 2010 two thirds of the steel produced in the U.S. was manufactured using ferrous scrap not mined ore [19]. Also the level of steel recycling reported in the US was at 84%, nearly all the material supply chain needs for steel.

Comminution and recycling of large items such as automobiles are both processes which reduce of solids into smaller particles. Comminution reduces ore bearing rock to smaller particles and recycling shreds large, solid objects such as vehicles. It is in the reduction of solids, where similarities between mining and material recycling occur, because similar, high energy use equipment is used.

Crushing is a technology used in the large product recycling industry, with a specific example being automotive recycling. Shredders using this principle are now manufactured in sizes ranging from 370 kW to 4,440 kW [20]. One of the earliest shredders was the Newell shredder. An example is shown in figure 6.

Castro [21] demonstrated, with a simulation model, how comminution in the recycling process can be considered to be similar to the comminution in mining. In effect, recycled End-of-Life (EOL) products can be considered as industrial ores having a concentration of metals that are recovered and processed in a similar manner to processing and refining in mining.

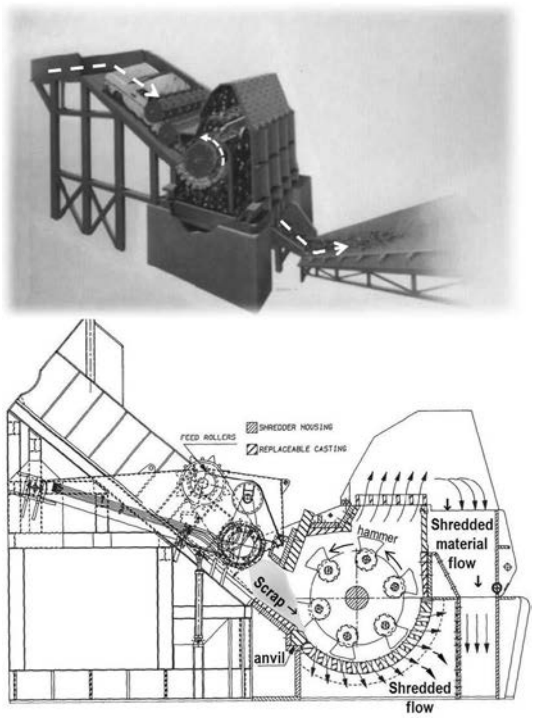


Figure 6. Newell hammer mill – shredder [20].

## 5. Assessing Mining

Knowing the energy consumption for mining, at both the extraction stage [22] and the crushing and grinding stage, the impact of energy use in mining can start to be assessed. Figure 7 is an illustration of how this can be done using SLCA.

The four parts of the value chain are: exploration, extraction, processing, refining. Four columns are shown in figure 7 under each of the value chain sections, for instance exploration, shows the five premanufacture stressors from Graedel's SLCA matrix [2]. Criticality is included as it is part of the ongoing debate of whether materials should be included in such a list. Aesthetic, which is a Grand Objective [2] has been included because mines have a negative visual impact upon a landscape.

The SLCA method used by Graedel is proposed. Each matrix element is valued from 0 (poor) to 4 (very good), as discussed in section 1.1.

Evaluations can be made in many ways, across the whole mining spectrum for a company, including all mining stages, or for each mining stage, exploration, extraction and refining or for a specific mine.

Environmental stressors, shown as vertical columns below each mining stage, are weighted and combined into a final evaluation for the each ER matrix. If each ER (environmentally responsible matrix) is given a maximum value of 20, then the maximum for a complete assessment is 100, and ratings can be viewed in percent.

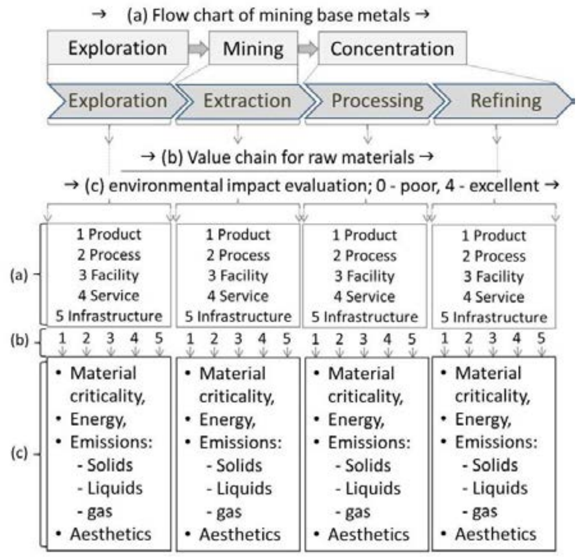


Figure 7. Evaluating mining with SLCA: each column (a) shows 5 stages. Row (b) shows all stages, 1 to 5 for each stage. Rows (c) show stressors.

## 6. Applying SLCA matrices

Each ER matrix has two dimensions: stages and stressors. The stressors are the same all. However, life cycle stages differ. Product life cycles have five sequential stages: mining → manufacture → delivery → use → disposal. Process life cycles matrices, figure 8a, have 2 parallel stages, 1a and 1b, 2a and 2b, with disposal at the end, as shown in figure 8b.

*Environmentally Responsible Process Matrix, ERP*

| Stressor → / Stage ↓ | *Materials Choice* | *Energy Use* | *Solid Residues* | *Liquid Residues* | *Gaseous Residues* |
|---|---|---|---|---|---|
| *1a. Process Provisioning* | 1,1 | 1,2 | 1,3 | 1,4 | 1,5 |
| *1b. Process Implementation* | 2,1 | 2,2 | 2,3 | 2,4 | 2,5 |
| *2a. Primary process operation* | 3,1 | 3,2 | 3,3 | 3,4 | 3,5 |
| *2b. Complimentary process* | 4,1 | 4,2 | 4,3 | 4,4 | 4,5 |
| *3. Disposal* | 5,1 | 5,2 | 5,3 | 5,4 | 5,5 |

(a)

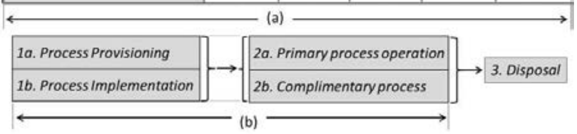


Figure 8. A typical process matrix.

Energy considerations for a process matrix include: process provisioning (1a), including energy to recover and recycle comminution media; implementation (1a), includes activities required to make comminution occur; for operation (2a), comminution; for complimentary processes such as preparing comminution media. Comminution, (2a) is has the large impact.

## 6. Example

Usually grinding is one of the largest, single energy consumers in mining, hence it offers one of the better opportunities for net energy efficiency improvements. Comminution alone can account for 60% of mine electrical power load and more than 35% of the operation's greenhouse gas emissions [23].

### 6.1 Case 1

In this example, a company operates 26 mines with 19 of the 26 using SAG (semi-autogenous grinding) and Ball mills, with power capabilities of up to 12,000 kW [24]. In successful efforts to reduce both energy consumption and $CO_2$ emissions at four mines, there was a 20% net energy improvement leading to a net $CO_2$ reduction of 43,000 tonnes per year or ≈21,000 tonnes of $CO_2$ per mine per year. This means a company-wide reduction of 19 x 21,000 tonnes $CO_2$ = 399,000 tonnes $CO_2$. This is a substantial reduction and should be evaluated at least as 2 or 3 out of 4 for the energy stressor (cell 3,2) in figure 8a.

The benefit is not only substantially decreased $CO_2$ emissions, but also increased energy efficiency of grinding processes, saving over $15 million a year in energy costs [23]. The reduction in carbon emissions should be given credit in the assessment, instead of rating mining as a 0, which designers do if mining is involved. This also illustrates the financial benefit in decreasing environmental impacts.

The values shown above should be used as a reference in the next iteration of an LCA when it is conducted.

### 6.2 Case 2

In this example a mine, both open pit and underground at the same site, is located in an extremely remote region in the arctic [25]. The mine fulfills one important role with respect to the three pillars of sustainability, it provides social and economic benefits to the local aboriginal population. For the foregoing reason, the facility, service and infrastructure cells can be rated above 0, with the proviso that minimum damage is to the regional environment and a plan is in place for rejuvenating the mine area once mining ceases.

Energy demands at this remote mine was by diesel fuel. However, four 2.3 MW wind turbines were installed by the company (9.3 MW total). The turbines produced 52% of mine energy needs, substantially reducing total mine $CO_2$ emissions, which included comminution emissions.

The kind of effort must be rewarded when completing product, process and facility assessments. For instance, 3 out of 4 is warranted for cell (1,2) in figure 8a.

The installation of wind turbines also gives a better rating to

## 7. Conclusion

There is considerable information in the literature about the technical aspects of comminution. It is not the intent of this paper about how to calculate and predict particle size with empirically derived equations.

Increasing the energy efficiency of grinding processes for crushing and grinding in mining has been discussed. Typical equipment used for these stages of mining has been illustrated and provides the designer with an understanding of what happens at these stages.

A comparison of energy use and equipment, between mining and recycling of large product items has been illustrated. For instance the energy needs for a car shredder is of the same order of magnitude as those of an average ball mill or SAG mill. The evaluation of energy use in mining, using the Graedel method for SLCA, usually gives a low rating. However, energy use can be very similar to the recycling of heavy metal products in recycling, such as cars.

Understanding how energy is consumed in mining will give LCA assessors a better understanding of how to evaluate the energy consumption in mining versus energy consumption in recycling at stage 1.

Designers need to assess product and process for mining taking into account reduction in energy use and carbon emissions. This paper has given a few examples.

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