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Emergy as a Life Cycle Impact Assessment Indicator: A Gold Mining Case Study

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Supporting information is available on the *JIE* Web site

Summary

Founded in thermodynamics and systems ecology, emergy evaluation is a method to associate a product with its dependencies on all upstream environmental and resource flows using a common unit of energy. Emergy is thus proposed as an indicator of aggregate resource use for life cycle assessment (LCA). An LCA of gold mining, based on an original life cycle inventory of a large gold mine in Peru, is used to demonstrate how emergy can be incorporated as an impact indicator into a process-based LCA model. The results demonstrate the usefulness of emergy in the LCA context. The adaptation of emergy evaluation, traditionally performed outside of the LCA framework, requires changes to the conventional accounting rules and the incorporation of uncertainty estimations of the emergy conversion factors, or unit emergy values. At the same time, traditional LCA boundaries are extended to incorporate the environmental processes that provide for raw resources, including ores. The total environmental contribution to the product, doré, is dominated by mining and metallurgical processes and not the geological processes forming the gold ore. The measure of environmental contribution to 1 gram (g) of doré is 6.8E + 12 solar-equivalent Joules (sej) and can be considered accurate within a factor of 2. These results are useful in assessing a process in light of available resources, which is essential to measuring long-term sustainability. Comparisons are made between emergy and other measures of resource use, and recommendations are made for future incorporation of emergy into LCA that will result in greater consistency with existing life cycle inventory (LCI) databases and other LCA indicators.

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Introduction

Life cycle assessment (LCA) is an established and widely utilized approach to evaluating environmental burdens associated with production activities. Emergy synthesis has been used for similar ends, although in an emergy synthesis one tracks a single, all-encompassing environmental attribute, a measure of embodied energy (Odum 1996). Although each is a developed methodology of environmental accounting, they are not mutually exclusive.

Emergy in the Life Cycle Assessment Context

LCA is a flexible framework that continues to grow to integrate new and revised indicators of impact, as determined by their relevance to the LCA purpose and the scientific validity of the indicator sets (ISO 2006a). Other thermodynamically based methods, such as exergy, have been integrated into LCA (Ayres et al. 1998; Bösch et al. 2007). Emergy synthesis offers original information about the relationship between a product or process and the environment that is not captured by existing LCA indicators, particularly relevant to resource use and long-term sustainability, which could be valuable for LCA. There are, however, differences in the conventions, systems boundaries, and allocation rules between emergy and LCA that require adjustments from the conventional application of emergy to achieve a consistent integration.

From the perspective of the LCA practitioner, the first questions regarding use of emergy are those of its utility. Why would one select emergy in lieu of or in addition to other indicators of environmental impact? For what purposes defined for an LCA study is emergy an appropriate metric? If we assume the inclusion of emergy as an indicator, what is necessary for its integration into the LCA framework? This article briefly describes the utility of emergy and, through a case study evaluation of a gold mining operation at Yanacocha, Peru, presents one example of how emergy can be used in an LCA framework. Finally, the theoretical and technical challenges posed by integration are discussed.

In reference to the first question, these three key points provide a theoretical justification for the use of emergy in LCA:

1. **Emergy offers the most extensive measure of energy requirements**. System boundaries in a cradle-to-gate LCA typically begin with an initial unit process in which a raw material is acquired (e.g., extraction) and include raw materials entering into that process but do not include any information on the environmental processes[1] creating those raw materials. Emergy traces energy inputs back further into the life cycle than any other thermodynamic method, summing life cycle energy inputs using the common denominator of the solar energy that directly and indirectly drives all biosphere processes (figure 1).[2] This energy could also be conceived as the energy requirements underlying at least some of the ecosystems services used in a process (Zhang et al. 2010a). Other thermodynamic methods, including exergy, do not include energy requirements underlying environmental processes (Ukidwe and Bakshi 2004).
2. **Emergy approximates the work of the environment to replace what is used**. When a resource is consumed in a production process, more energy is required to regenerate or replenish that resource. The emergy of a resource is the energy required to make it, including work of the environment and assuming equivalent conditions; this *is* the energy that it takes to replenish the resource. Sustainability ultimately requires that inputs and outputs to the biosphere or its subsystems balance out (Gallopin 2003). As the only measure that relates products to energy inputs into the biosphere required to create them, emergy relates consumption to ultimate limits in the biosphere by quantifying the additional work it would require from nature to replace the consumed resources.
3. **Emergy presents a unified measure of resource use**. Comparing the impacts of use of biotic versus abiotic resources or

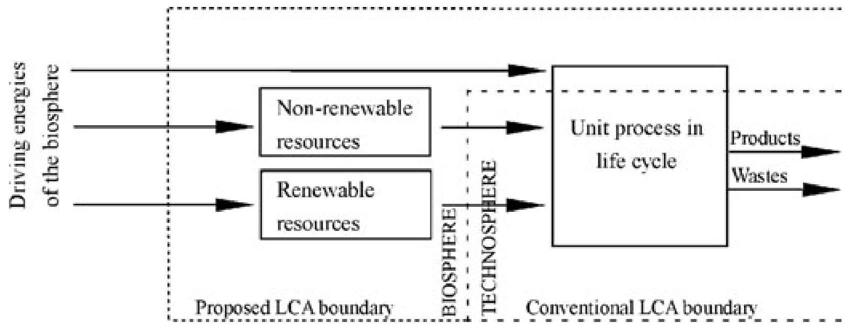

Figure 1 Proposed boundary expansion of life cycle assessment (LCA) with emergy. Driving energies include, for example, sunlight, rain, wind, deep heat, and tidal flow.

renewable versus nonrenewable resources typically necessitates some sort of weighting scheme for comparison. Because there is less agreement on characterization of biotic resources, these may not be included, despite their potential relevance (Guinée 2002).[3] In emergy, abiotic and biotic resources are both included and measured with the same units. As follows from its nature as a unified indicator, one that characterizes inputs with a single methodology to relate them with one unit (emergy uses solar emjoules [sejs], which are solar-equivalent joules), no weighting scheme is necessary to join different forms of resources (e.g., renewable and nonrenewable; fuels and minerals) to interpret the results.

The choice of measures of impact in an LCA follow from the goal and scope of the study (ISO 2006a). Emergy analyses have been used for a multitude of LCA-related purposes, including to measure cumulative energy consumption (Federici et al. 2008), to compare environmental performance of process alternatives (La Rosa et al. 2008), to create indexes for measuring sustainability (Brown and Ulgiati 1997), to quantify the resource base of ecosystems (Tilley 2003), to measure environmental carrying capacity (Cuadra and Björklund 2007), and for nonmarket-based valuation (Odum and Odum 2000). The incorporation of emergy in LCA could enhance the ability of LCA studies to achieve these and other purposes.

This is not the first study to attempt to combine emergy and LCA. Earlier studies focused on contrasting the two approaches (Pizzigallo et al. 2008) or extending emergy to include disposal and recycling processes (Brown and Buranakarn 2003). The most comprehensive approaches probably include the Eco-LCA and SUMMA models. Although referred to as ecological cumulative exergy consumption (ECEC) rather than emergy due to some slight modifications to emergy algebra, the Eco-LCA model is an enhanced input-output LCA model that uses emergy as an impact indicator (Urban and Bakshi 2009; Zhang et al. 2010b). The SUMMA model is a multicriteria analysis tool that uses emergy as one measure of "upstream" impact, which it combines with other measures of downstream impact (Ulgiati et al. 2006). A similar multicriteria approach using MFA, embodied energy, exergy, and emergy is used by Cherubini and colleagues (2009).

In contrast with these previous studies, the present study draws on a more conventional process-based LCA approach using common industry software (SimaPro; PRé Consultants, 2008) and attempts to integrate emergy as an indicator within that framework, as specified by the ISO 14040/44 standards, which results in adjustments to the conventional emergy methodology. This is also the first study to use emergy in a detailed process LCA in which flows are tracked at a unit process level. Results from the study, addressed in the Discussion section, reveal insights for which emergy is suggested to be a useful metric for LCA.

A Case Study of Emergy in a Life Cycle Analysis of Gold-Silver Bullion Production

Metals and their related mining and metallurgical processes have been a frequent subject of LCA and other studies using approaches from industrial ecology (e.g., Dubreuil 2005; Yellishetty et al. 2009), which is reflective of the critical dependence of society on metals as well as an acknowledgement of the potential environmental consequences of their life cycles. Although these studies have addressed both downstream and upstream impacts, including resource consumption, none has used tools capable of connecting the product system to the environmental processes that provide for the raw resources they require (especially because they are largely nonrenewable). An LCA is presented here of a gold-silver mining operation that uses emergy to quantify the dependence on environmental flows. In this case study, the primary purpose could be succinctly stated as follows: to quantify the total environmental contribution underlying production of gold-silver bullion at the Yanacocha mine in Peru.[4]

Total environmental contribution includes the total work required by the environment (biosphere) and the human-dominated systems it supports (technosphere) to provide for that product. As impacts in LCA are categorized as resource-related (which refers to upstream impacts) or pollution-related (which refers to downstream impacts; Bare et al. 2003), environmental contribution is categorized with the former.

The scope of this study, following from this goal, extends from the formation of the gold deposit (which represents the work of the environment) to the production of the semirefined doré, a bar of mixed gold and silver.[5] Emergy is chosen as the measure of environmental contribution, to be tracked over this "cradle-to-gate" study and to be the basis of the indicator of the impact of mining. Energy is commonly used in LCA to track the total energy supplied to drive processes in an industrial life cycle. Yet the interest here is in how much work was done in both environmental systems and human-dominated systems to provide for it (point 2), which is not measured just through a consideration of available energy used by energy carriers (e.g., cumulative energy demand) or as the sum of all available energy (exergy) in all the inputs (point 1). Additionally, the energy from the environment to provide for nonenergy resources (materials) is part of the environmental contribution (point 2), so all need to be tracked. To directly compare the environmental contribution underlying each resource input, together with the others contributing to a unit process of mining operation, however, the contribution should be tracked with a single indicator; which emergy serves as here (point 3).

Using emergy allows for the introduction of more specific questions, which, when used in an LCA context, are answerable where they are traditionally not in an emergy evaluation, which lumps all inputs into a single system process. The ability to track unit processes from the biosphere together with unit processes in the technosphere enables one to ask the following question:

1. Is there more environmental contribution underlying the formation of the gold or the combined mining processes?

as well as the more familiar (to LCA) comparisons of inputs and unit processes in the product system:

2. Which unit processes are the most intensive in terms of environmental contribution?
3. Which inputs are responsible for this?

To address long-term sustainability, one can put the activity surrounding this life cycle in the context of available resources; that is,

4. How does this relate to the availability of energy driving environmental processes in this region?

LCA results should be presented with accompanying uncertainty quantified to the extent feasible (ISO 2006b). To fit in the LCA framework, emergy results also need to be presented with uncertainty estimations to explain the accuracy with which the environmental contribution can be predicted.

Gold and silver are coproducts that may be mined separately and that have independent end uses, so comparing these life cycle data with alternative production routes requires allocating environmental contribution between gold, silver, and also mercury, which is naturally associated with the ore body, separated during the refining stage and sold as a by-product.

This LCA is not comparative, because no other alternative solutions for providing the gold are being evaluated. Nevertheless, with a universal measure of impact that does not require normalization or weighting (point 4), results can be compared with alternative product systems for which emergy evaluation has been done, if the boundaries and allocation rules for these alternative products are comparable, or put in the context of other relevant emergy flows, such as those supporting ecosystems or economic systems in the same region.

Methodology

The functional unit chosen for the study is 1 gram (g) of doré (gold-silver bullion) at the mine gate, consisting of 43.4% gold and 56.6% silver. For comparison with other gold, silver, and mercury products, results are also reported in relation to 1 g of gold, 1 g of silver, and 1 g of mercury. The inventory for these products was based on the average of annual production in 2005, the most recent year for which all necessary data were available. Annual production was reported by one of the mine partners (Buenaventura Mining Company Inc. 2006). The total production for this year was approximately 9.40E + 04[6] kg of gold and 1.23E + 05 kg of silver combined as gold-silver bullion, or doré.

A process-based inventory was completed in accordance with the ISO 14040 series standards (ISO 2006a, 2006b) and included direct inputs from the environment (elementary flows), capital and nondurable goods, fuels, electricity, and transportation, along with inputs not traditionally or commonly accounted for, including the geologic contribution to mineral formation. Nine unit processes representing process stages were defined, and inputs were tracked by unit process (figure 2). These were divided into background processes (deposit formation, exploration, and mine infrastructure), production processes (extraction, leaching, and processing), and auxiliary processes (water treatment, sediment control, and reclamation). A description of the inventory calculations and results is found in Supporting Information S2 on the Journal's Web site.

Emergy and Energy Calculations

All inputs were converted into emergy values either according to original emergy calculations or by use of previously calculated unit emergy values that relate input flows in the inventory to emergy values (UEV) (Odum 1996). An inventory cutoff for inputs consisting of 99% of the emergy for the process was declared, which was as comprehensive as possible without including all minor inputs. As the emergy of some inputs was not readily estimated prior to the inventory collection, these inputs were by default included and, even if determined to contribute less than 1% of the total emergy, were kept in the inventory.

The geologic emergy of gold, silver, and mercury (which represents the work of the environment in the placement of mineable deposits) was estimated according to the method of Cohen and colleagues (2008), who proposed a new universal model for estimating emergy in elemental metals in the ground, based on an enrichment ratio of the element, which can be described in the form:

$$UEV_i = ER_i^{*} 1.68\text{E} + 09 \text{ sej/g} \qquad (1)$$

where UEV_i is the unit emergy value (in sej/g) of element i in the ground and ER_i is the enrichment ratio of element i. The ER can be estimated with the following equation:

$$ER_i = \text{OGC}_i / \text{CC}_i \qquad (2)$$

where OGC_i is the ore grade cutoff of element i, which is the current minimal mineable concentration, and CC_i is the crustal background concentration of that element. This model assumes that ores with greater concentrations of metals require greater geologic work to form, without attempting to mechanistically model the diverse and random geological processes at work, which confers a general advantage of consistent and comparable emergy estimations for all mined metals. This universal method provides average UEVs for a particular metal in the ground but was adapted here with the specific concentrations of

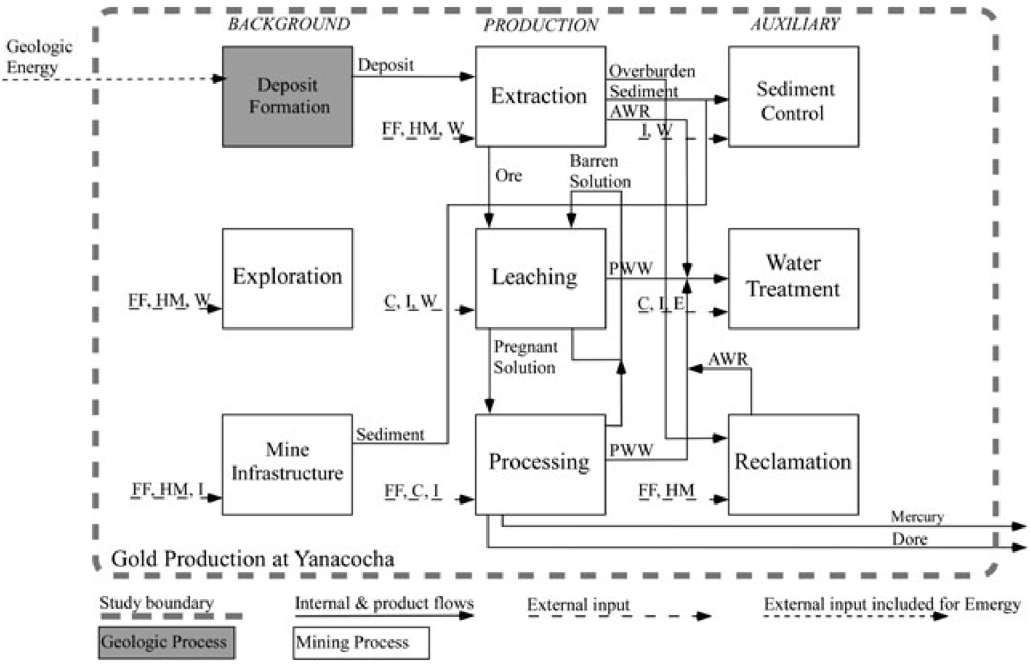

Figure 2 Gold production system at Yanacocha with modeled flows and unit processes. FF = fossil fuels; HM = heavy machinery; I = infrastructure; C = chemicals; W = precipitation and pumped water; E = electricity; AWR = acid water runoff; PWW = process wastewater.

gold, silver, and mercury at Yanacocha in place of the OGC for those elements.

Original emergy calculations were necessary for a number of mining inputs, including mine vehicles, chemicals, mine infrastructure, and transportation. When available, data on these inputs were adapted from a commercial life cycle inventory database, Ecoinvent v2.0 (Ecoinvent Centre 2007), and copied into a new process. Inputs for these processes were replaced by processes carrying UEVs calculated from previously published emergy analyses. When the processes were adapted from Ecoinvent, emissions, infrastructure, and transportation data were not included, the latter of which was determined to be inappropriate for the mine location and was calculated independently or estimated to be insignificant. For chemicals not available in Ecoinvent, synthesis processes were based on stochiometry found in literature references, and primary material inputs as well as energy sources were included. Emergy in overseas shipping and transportation within Peru of inputs was estimated for all materials comprising 99% of the total mass of inputs to the process.

The global baseline (estimate of emergy driving a planet and basis of all emergy estimates) of 15.83E + 24 sej/yr was used for all original UEV calculations (Odum et al. 2000) and for updates of all existing UEVs calculated in other studies. When available, existing UEVs were incorporated without labor or services, for consistency with the Ecoinvent data used, which do not include labor inputs to processes. For comparison with emergy values, primary energy was estimated as the sum of the total energy content of fossil fuels and electricity consumed on site, given energy values from the cumulative energy demand characterization method as implemented in SimaPro (Frischknecht and Jungbluth 2007).

Uncertainty Modeling

Uncertainty was present at the inventory level (e.g., inputs to mining) and for the unit emergy values (the UEVs) used to convert those data into emergy. Uncertainty data for both direct inputs and UEV values (existing and original) were included in the life cycle model. Quantities of direct inputs to one of the nine unit processes were assigned a range of uncertainty on the basis of the same model defined for the Ecoinvent database (Frischknecht et al. 2007). This model assumes data fit a log-normal distribution. With this model, the geometric variance was estimated for each input. Calculations of uncertainty ranges for the UEVs for inputs to the process were estimated on the basis of a UEV uncertainty model (Ingwersen 2010). This model produces 95% confidence intervals for UEVs, also based on a lognormal distribution, and is described in the form of the geometric mean (median) times/divided by the geometric variance, abbreviated in the following form:

$$\mu_{\text{geo}}(x\div)\sigma^2_{\text{geo}} \tag{3}$$

where μ_{geo} is the geometric mean or median and σ^2_{geo} is the geometric variance. The bounds of the 95% confidence interval are defined such that the lower bound is equal to the median divided by the geometric variance, and the upper bound is the median multiplied by the geometric variance. Original uncertainty estimations based on the analytical method (Ingwersen 2010) were performed for gold and silver in the ground.

Allocation

Two allocation approaches were adopted: the coproduct rule often used in emergy analysis, and a by-product economic allocation rule used when applicable in LCA. The coproduct rule assumes that each product—in this case gold, silver, and mercury—requires the total emergy of the mining processes for its production, and therefore the total mining emergy is allocated to each. Economic allocation is one method in LCA in which an environmental impact is divided among multiple products. Economic allocation was selected here in preference to allocation by mass because it most closely reflects the motivations of coproduct metal producers (Weidema and Norris 2002). In this case, revenue from production was used to allocate environmental contribution, through determination of the market value of the gold contained in the doré as a percentage of the total value of doré and mercury production. The resulting percentage was used as the percentage of total mining emergy allocated to gold. The same method was applied for silver and mercury. In both cases, geologic emergy was allocated to each product separately, because the model used for estimating geologic emergy in the products was element-specific.

Data Management and Tools

All inventory data were stored in SimaPro 7.1 LCA software (PRé Consultants 2008). A new process was created for each input. Emergy was entered as a "substance" in the substance library, and a new unit "sej" was defined in the unit library and given the equivalent of 1 Joule.[7] This unit was assigned to the emergy substance. When existing UEVs were relied on (e.g., for refined oil), a "system" process was created, for which emergy was the only input. A quantity of emergy in solar emjoules was assigned to the output that corresponded with the unit emergy value (sej/g, sej/J, etc.). For inputs for which UEV values did not exist or were not appropriate, "unit" processes were created that consisted of one or more system processes or other unit processes.[8] A new impact method was defined to sum life cycle emergy of all inputs to a process. To characterize total uncertainty (both input and UEV uncertainty) in the emergy of the mining products, Monte Carlo simulations of 1,000 iterations were run in SimaPro for estimates of confidence intervals of emergy in the products using both emergy coproduct and economic allocation rules.

Results

Environmental Contribution to Gold, Silver, and Mercury in the Ground

The enrichment ratio of gold was estimated as 218.8:1, on the basis of a reported gold concentration of 0.87 parts per million (ppm; Buenaventura Mining Company Inc. 2006) and a crustal background concentration of 4 parts per billion (ppb; Butterman and Amey 2005); this ratio, as per equation (1), resulted in a unit emergy value for gold in the ground of 3.65E + 11 solar emjoules per gram (sej/g). The silver concentration at the mine was not reported but was estimated on the basis of the silver in the product and a calculated recovery rate of gold (81.52%) to be 1.13 ppm. Given the background concentration of 0.075 ppm (Butterman and Hilliard 2004), the enrichment ratio of silver was estimated as 15.1:1, which resulted in an estimate of the UEV of silver in the ground at Yanacocha to be 1.54E + 10 sej/g. The emergy of mercury in the ground was estimated to be 1.71E + 11 sej/g, on the basis of a concentration at the mine of 8.6 ppm (Stratus Consulting 2003) and a crustal background concentration of 0.085 ppm (Ehrlich and Newman 2008). The total emergy in the amount of gold extracted and transformed into doré in 2005, just including the geologic contribution to gold in the ground, was 8.55E + 18 (x÷)10.7 sej (median times or divided by the geometric variance, as in equation 3).

Environmental Contribution to Doré

Table 1 shows the results of the total emergy in the mining products including for the doré, the gold and silver separately, and the mercury by-product. The total emergy in all the life cycle stages contributing to 1 g of doré was approximately 6.8E+12 sej, with an approximate confidence interval of 6.2E+12(x÷) 2.0. The primary sources of emergy in the product are depicted in figure 3. When we consider estimated uncertainty both in the inventory data and in the unit emergy values, the emergy in doré could, with 95% confidence, be predicted to be as low as 4.4 E+12 sej/g and as high as 1.3E+13 sej/g, which represents an approximate range of a factor of 2 around the median value.

As a portion of the contribution to the total emergy in the doré, the geologic emergy in deposit formation contributes approximately 3% (figure 3) but could be as high as 7% if the highest value in the range is used. The largest contributors to the total emergy of the doré included chemicals (42%), followed by fossil fuels (32%) and electricity (14%). Capital goods (mine infrastructure and heavy equipment) contribute 5%.

Relative emergy contribution of inputs is not well associated with input mass because of differences in the unit emergy values of inputs to the process. Chemicals used in the process illustrate this difference. A minor input by mass used in the processing stage, lead acetate, contributed more emergy than did lime, whose mass input was 267 times greater.

Emergy by Unit Process

Researchers do not typically break down the life cycle of a product into unit processes in emergy analysis, but this is a common step of interpretation in an LCA. Analyzing process

Table 1 Summary of emergy in mine products based on two allocation rules.

Product	*Geologic emergy*	*Mining emergy*	*Mining allocation %*	*Total emergy*	*95% confidence interval*		
Emergy based on coproduct allocation							
Doré	1.7E+11	6.6E+12	100	6.8E+12	4.4E+12	–	1.3E+13
Gold in doré	3.7E+11	1.5E+13	100	1.6E+13	1.0E+13	–	2.7E+13
Silver in doré	2.5E+10	1.2E+13	100	1.2E+13	7.5E+12	–	2.2E+13
Mercury	1.7E+11	2.4E+13	100	2.4E+13	1.6E+13	–	4.5E+13
Emergy based on economic allocation[a]							
Doré	1.7E+11	6.6E+12	99.92	6.8E+12	4.4E+12	–	1.3E+13
Gold in doré	3.7E+11	1.5E+13	97.31	1.5E+13	9.9E+12	–	2.5E+13
Silver in doré	2.5E+10	3.0E+11	2.61	3.3E+11	2.2E+11	–	5.4E+11
Mercury	1.7E+11	2.0E+10	0.08	1.9E+11	1.8E+11	–	2.1E+11

Note: All units are in solar emjoules per gram (sej/g).
[a]Based on 2005 gold and silver price received of $12.69/g and $0.26/g (Buenaventura 2006); mercury market price of $0.02/g (Metalprices.com).

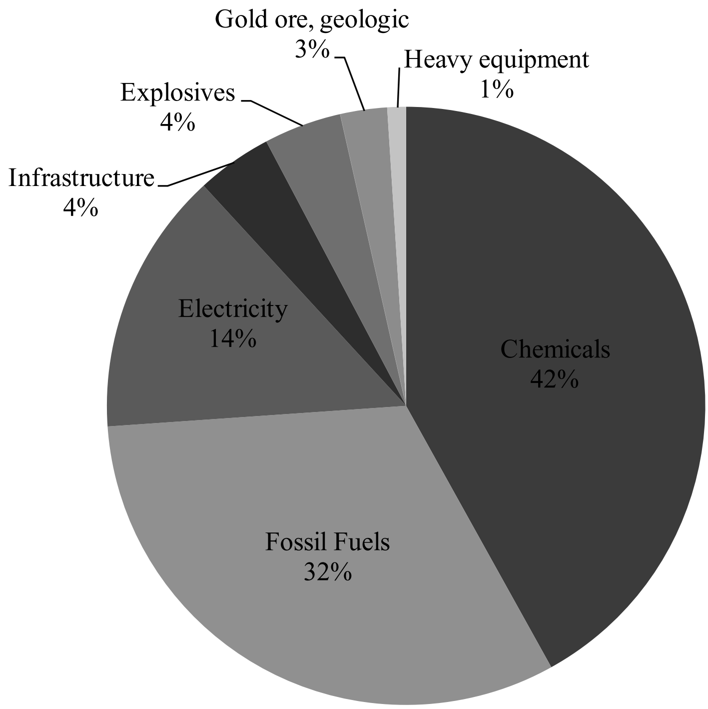

Figure 3 Environmental contribution (emergy) to doré by input type.

contribution can help target where in the life cycle environmental burdens are greatest. Figure 4 shows the breakdown of emergy and primary energy by mining unit process.

The largest environmental contribution comes from the extraction process. Extraction emergy is dominated by diesel fuel consumed by mine vehicles. The other production processes

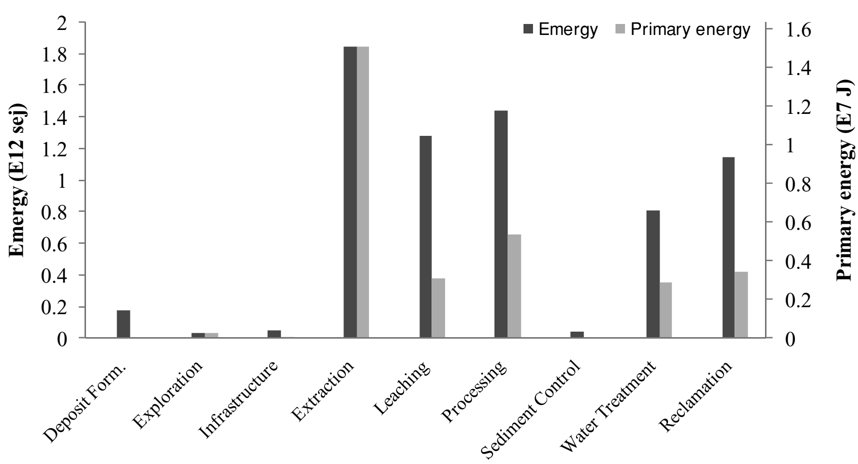

Figure 4 Emergy and primary energy in 1 gram (g) of doré by unit process. Primary energy is depicted on a second axis, which is adjusted so that emergy and primary energy in extraction appear the same, so the relative contribution of each to processes can be depicted. sej = solar emjoules; J = joules; Form. = formation.

are chemically intensive. Together, the production processes represent 67% of the total emergy. Controlling for pollution to air, water, and soil, which is the objective of the auxiliary processes, contributes about 30% of the total emergy. Background processes contribute little (less than 4%) to the emergy in the doré.

Figure 4 reveals differences in the absolute and relative contributions to processes, as indicated by emergy and primary energy. First, the emergy for each process is six orders of magnitude greater than the primary energy in each process. Additionally, the contributions of the nonextraction processes are relatively greater when measured in emergy than when measured with primary energy. Primary energy reveals no use of energy in the deposit formation process and relatively less energy in processes that are more chemically and materially intensive.

Allocation and Emergy Uncertainty

Table 1 presents the differences in the gold, silver, and mercury UEVs according to the two different allocation rules used. Because of its high value, under the economic allocation rule the gold product is allocated 97.3% of the emergy, which results in a UEV similar to that calculated under the coproduct scheme, in which it is allocated 100%. The big difference appears in the calculations of the UEVs for silver and mercury (3E + 11 and 1.9E11 sej/g), because they are allocated small portions of the total emergy (2.61% and 0.08%). This reduces the silver UEV to 2.8% of the coproduct value and reduces the mercury UEV to only 0.8% of the coproduct value.

Uncertainties in process inputs vary on the basis of uncertainty in the inventory data but are primarily due to the uncertainty of the UEVs.[9] The inputs with the greatest range of UEV values are the minerals and inorganic chemicals that are mineral based (see ranges in Table S1–2 of Supporting Information S1 on the Web). In comparison, uncertainty σ^2_{geo} values were between 1 and 1.5 for most inputs in the inventory. Figure 5 shows the results of the Monte Carlo analysis of the emergy in 1 g of doré, illustrating the resulting uncertainty range for the doré product. The distribution is right-skewed and resembles a log-normal distribution. Overall, the combined uncertainties in the inputs lead to less uncertainty in the doré (a factor of 2) than some of the major inputs (e.g., gold in the ground with a factor of 10).

Discussion

Usefulness of Emergy Results

A significant finding of this LCA is that the environmental contribution to the mining process, dominated by fuels and chemicals, was

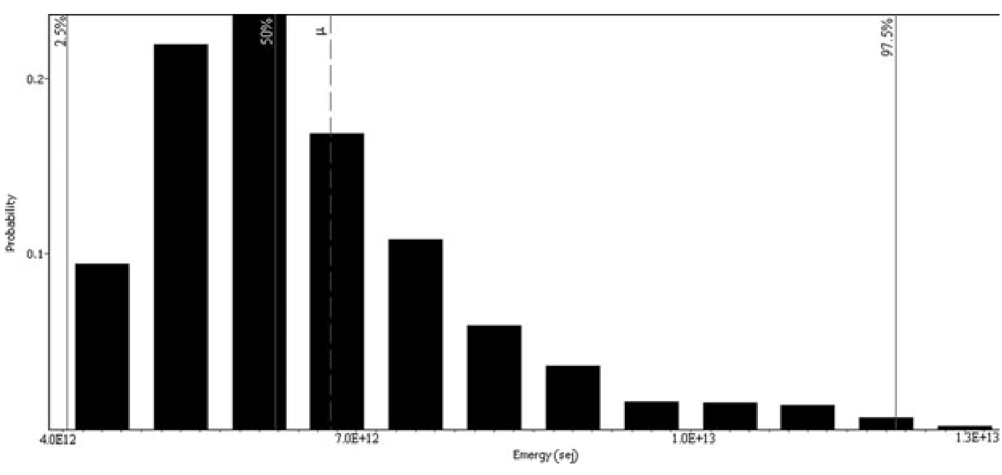

Figure 5 Monte Carlo analysis of 1 gram (g) of doré, showing the tails and center of the 95% confidence interval (CI), along with the mean (dashed line). sej = solar emjoules.

estimated to be greater than the contribution to the formation of the gold itself. This result holds despite the large uncertainty associated with quantification of the environmental contribution to gold in the ground. The production of doré can also be interpreted to be a process with a net emergy loss, with an emergy yield ratio (EYR) of close to 1, because the emergy expended in making the product (represented here by the mining processes) is greater than the emergy embodied in the raw resource.[10] This is unfavorable in comparison with fossil energy sources and other primary sector products, which generally have emergy yield ratios greater than 2 (Brown et al. 2009), but this finding provides no insight into the utility of the resource in society, which is much different in function and lifetime than these other products.

Although primary energy would indicate that the energy in mining is heavily dominated by fuel consumption during extraction, using emergy as an indicator shows that the other, more chemically and capital-intensive processes weigh more significantly and therefore that reducing the total environmental contribution to the process would demand a broader look at the other processes and inputs. This is consistent with the trends in the results that Franzese and colleagues (2009) obtained in their comparison of gross energy and emergy in biomass.

Quantifying resource use in emergy units permits us to put processes in the context of the flows of available renewable resources. Emergy used in a process can be seen as the liquidation of stocks of accumulated renewable energy in all the inputs to that process. The limit of sustainability, in emergy terms, is such that total emergy used by society should be less than or equal to the emergy driving the biosphere during the same period of time. Thus, the liquidation of the stock of emergy should not be greater than the flows of emergy. In this case, the amount of emergy in the doré (the stock) produced by the mine in 1 year is equivalent to approximately one-third of the emergy in sunlight falling on the nation of Peru in 1 year and one-third of 1% of the emergy in all the renewable resources available annually to Peru (Sweeney et al. 2008).[11] Although this does not represent a trade-off for the current period (because the stock of emergy in the doré was largely accumulated in a prior time period), it puts the total resource use in the process and the available flows of resources on the same scale, which is a step toward quantifying the sustainability of production. The Peruvian economy is driven, on average, by 35% renewable resources, but the mining process at Yanacocha itself is only approximately 3.5% renewable on a life cycle emergy basis.[12] This result should not come as a surprise, given that mining and other resource extraction activities largely use nonrenewable energy sources to extract nonrenewable resources.

The emergy in 1 g of doré is on the order of E + 12–13 sej/g. The eventual "London good" gold sold on the international market, which is produced by further refinement of the doré, will have a minimum emergy on the order of E + 13 sej/g. This is hundreds of times greater than that reported for products from other economic sectors, such as biomass-based products, chemicals, and plastics, which have UEVs consistent with the global emergy base used here, on the order of E + 8-E + 11 sej/g (Odum 1996), which reflects the high environmental contribution underlying gold products, consistent with the high market value of gold.

Emergy in Life Cycle Assessment: Challenges

The boundary, allocation, and other accounting differences between emergy and LCA were dealt with here in a progressive manner. The system boundary was expanded beyond traditional LCA to include flows of energy underlying the creation of resources used as inputs to the foreground and background processes. The inventory of the gold mining process involved a hybridization of background data from previous emergy analyses as well as data from an LCI database. Numerous challenges remain for a theoretically and procedurally consistent integration of emergy and LCA; these challenges are discussed here.

Challenges of Using Emergy With Life Cycle Inventory Databases and Software

This study reveals some of the complexities and potential inconsistencies of integrating emergy into LCA, particularly if one wants to use emergy along with other life cycle impact assessment (LCIA) indicators and to be consistent in the use of accounting rules. The technical integration of emergy for the characterization of some of the processes (e.g., inventories for processes occurring off-site) implemented here in SimaPro had the shortcoming of not being able to comparatively measure other environmental aspects from background processes in the life cycle. For some of these inputs for which emergy evaluations already existed (e.g., for stainless steel used in mine infrastructure and vehicles), emergy was the only input to the item, which made impossible computation of other full life cycle indicators for resources use (e.g., cumulative exergy demand). A better method of integrating emergy into an LCI is to associate emergy with substances and then allow the software to track the emergy through all the processes, rather than creating processes that store unit emergy values. Such a method would permit more accurate cross-comparison of emergy with other impact indicators.

Emergy evaluation conventionally incorporates the emergy embodied in human labor and services (Odum 1996). Labor may be added as an input in some forms in traditional LCA, such as in worker transportation (O'Brien et al. 2006), but energy in labor has largely been left out, and its inclusion represents a potential addition to LCA from the emergy field. As in a typical emergy evaluation, however, labor is not included in processes in existing LCI databases, including Ecoinvent 2.0. For this reason, labor was not included here. "Service" is the conventional means by which the labor of background processes is included in an emergy analysis. "Service" is the emergy in the dollars paid for process inputs, estimated according to an emergy:money ratio to represent the average emergy behind a unit of money; it represents labor in background processes on the basis of the assumption that money paid for goods and services eventually goes back to pay for the cost of human labor, because money never returns to the natural resources themselves (Odum 1996). Unit emergy values are often reported as "with labor and services" or "without labor and services." For consistent incorporation of emergy in labor in an LCA, labor would also need to be incorporated into the background processes drawn from LCI databases. Unless background processes can be "retrofitted" with labor estimations, unit emergy values used for LCA should be those "without labor and services." This will, however, result in the omission of an input that is considered to be integral to holistic accounting in emergy theory, because all technosphere products rely on human input.

Reconciling rules for allocation is another necessary step for inclusion of emergy in LCA. In the LCA context, the emergy coproduct allocation would be inconsistent and nonadditive, because the emergy in the products would be double-counted when they become inputs in the same system (which can be as large as the global economy). Thus, results based on this allocation rule should be recalculated according to an allocation rule that divides up emergy before it is used with existing LCIA calculation routines, to avoid the potential double-counting of emergy.[13] Allocation rules or alternatives to allocation typically used in LCA can easily be applied to allocate emergy among by-products and coproducts, as was demonstrated here, but if existing UEVs for coproducts are incorporated, they will have to be recalculated with the chosen allocation rule before incorporation.

Allocation is not just an issue among coproducts but is also an issue related to the end of life of many of the materials used. Although many of the inputs to doré were transformed in such a way that they were completely consumed (e.g., the refined oil is combusted), others, particularly the gold itself, were not consumed in such a manner. Gold can theoretically be infinitely recycled and is not generally consumed in its common uses (e.g., jewelry). In emergy evaluation of recycled products, the amount of emergy that goes into the formation of the resource would be retained (i.e., deposit formation) for the materials each time it is recycled (Brown and Buranakarn 2003). In contrast, it has been traditional practice for systems with open loop recycling (e.g., the metals industry) to split the total environmental impact among the number of distinct uses of a material (Gloria 2009). If this approach were used, it would require splitting the emergy of resource formation as well as the emergy of mining among the anticipated number of lifetime uses of the gold product. But allocation in systems with recycle loops is an unresolved issue in LCA, especially for products such as metals and minerals, and the problem is not limited to the context of integrating emergy into LCA (Yellishetty et al. 2009).

Energy in Environmental Support not Conventionally Included in Emergy Evaluation

Although emergy is more thorough than other resource use indicators in consideration of energy use from the environment, not all the energy required by the environment to support the doré product is included here. Geologic emergy in the clay and gravel used as a base layer for roads and the leach pads is not included, under the assumption that these materials are not consumed in the process. Additionally, there are waste flows from the mine, some of which, such as those potentially emanating from the process sludge and residuals on the leach pads, may occur over a long period of time following mine closure. These and contemporary emissions to air, water, and soil require energy to absorb, but these are not quantified here, as they are not typically quantified in emergy analysis. Other measures to quantify damage in this waste, although they may not be numerically consistent with the analysis here, could fill in the information gap, although, unless they are consistent with emergy units and methods, they will not allow for a single measure of impact. Traditional measures of impact used in LCA, such as global warming potential and freshwater aquatic ecotoxicity potential (Guinée 2002), could serve this purpose. More investigation needs to be done to relate emergy with other environmental impact metrics within the LCA framework. The outcome of emergy and other LCA metrics may not warrant the same management action, especially those LCA metrics that measure waste flows, as they are measures of effects on environmental sinks instead of use of sources.

Uncertainty in Unit Emergy Values

Emergy from geologic processes in scarce minerals is characterized by a high degree of uncertainty (around a factor of 10) relative to other products, largely due to the differences in different models used to estimate emergy in minerals (Ingwersen 2010). There is limited analysis of uncertainty in emergy values, however. The largely unquantified uncertainty associated with UEV values needs to be addressed so that use of emergy in LCA attributes appropriate uncertainty not just to inventory data but also to previous UEVs. The uncertainty of UEVs contributing 90% of the emergy was characterized in this article through a method proposed in other work by the author (2010). Using a model to estimate UEV uncertainty to couple with inventory uncertainty will help to better quantify uncertainty in LCA studies that use emergy, which will permit statistically robust comparison of emergy in products that serve the same function (e.g., comparative LCA).

Emergy and Other Resource Use Indicators

As integrated into LCA in this analysis, emergy is suggested as one measure of resource use, defined as environmental contribution. Although primary energy use was the only other resource use metric that was quantitatively compared with emergy in this study, it would be useful to see how emergy compares with other implemented and proposed indicators of resource use in LCA, namely indicators of abiotic resource depletion, direct material input, and cumulative energy demand as well as cumulative exergy demand. Such comparisons have been made possible by the EIO-LCA "eco-LCA" model, which reports mass, energy, exergy, and emergy-based indicators for products. In comparative analyses of bio-based versus petroleum-based production of a common polymer (Urban and Bakshi 2009) and paper versus plastic cups (Zhang et al. 2010b), the authors have demonstrated how including a measure of environmental contribution alongside these other resource use indicators provides unique insight into the environmental burden of products. This could be equally useful for process-based LCA models, such as the model described here.

Indicators of resource depletion are commonly used in LCA to represent how much of a particular resource is consumed in reference to its availability.[14] These are resource-specific indicators and depend on information on total reserves of various resources, which is not readily available.

Emergy is not often applied to assessing reserves, and it is not resource-specific. Use of emergy as proposed here is therefore not closely comparable with indicators of resource depletion, which, in cases of resource scarcity, convey very useful information on informing material selection.

Direct material input has been used as an indicator, particularly in the mining sector (e.g., Giljum 2004). It has also been argued to be of limited utility, however, primarily because it does not account for quality differences among resources and also includes resources that are not transformed or consumed in processes (e.g., overburden; Gössling-Reisemann 2008a). Emergy does take into account resource quality, on the basis of a principle that more embodied energy in creating a resource represents higher quality (Odum 1988).

Of the resource use indicators, emergy is seen by some as closely related with exergy (Hau and Bakshi 2004; Bastianoni et al. 2007). This is, in fact, only the case when conventional exergy analysis is expanded to include available energy in inputs from driving energies in the environment (figure 1). Otherwise, the boundaries for exergy consumption are like those in conventional LCA and still do not account for the energy driving environmental processes. Cumulative exergy consumption or a similar metric, entropy production (Gössling-Reisemann 2008a), are useful measures of efficient use of the available energy embodied in resources and thus relative measures of thermodynamic efficiency of systems, or ultimate measures of the depletion of the utility of resources in the process of providing a product or service (Bösch et al. 2007). Because of the similarity between exergy and emergy, one might expect redundant results when using both exergy-based indicators and emergy-based indicators. Nonetheless, a brief comparison of the result of applying the cumulative exergy demand (CExD) indicator to a product from the Ecoinvent database, "Gold, from combined gold-silver production, at refinery/PE U,"[15] to the emergy results here show some significant differences in the sources of exergy contribution in comparison with emergy contribution. Approximately 72% of the exergy in this product comes from electricity production, and 22% comes from the gold ore in the ground. In comparison with the results from this study (figure 2), emergy shows a much higher relative role of the fuels and chemicals used in the process.[16] This can be largely explained by the differences in the information that emergy and exergy provide. Exergy and entropy production more precisely measure embodied energy *consumption*, whereas emergy is a measure of energy throughput and could be better described as measuring *use* than consumption (Gössling-Reisemann 2008b). Also, exergy describes the available energy in substances (including the chemical energy in minerals), which is not the same as the amount of energy used directly and indirectly in their creation in the environment. In summary, the use of emergy provides unique information regarding resource use that does not make other resource use indicators, such as exergy, irrelevant but rather can augment the understanding of resource use by tailoring their use to address questions at different scales (Ulgiati et al. 2006). Emergy is, however, the only one of these measures that relates resources used in product life cycles back to the process in the environment necessary to replace those resources, and hence it is the best potential measure of the long-term environmental sustainability of production.

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Notes

1. All references to "environmental processes" and "environmental flows" in this article refer to solar, geologic, and hydrologic flows that sustain both ecosystems and human-dominated systems. This is the essence of what is meant here by "environmental contribution."

2. For example, growing corn requires the solar energy necessary to support photosynthesis of the corn plant. This includes all the solar energy falling on the corn field, not just the amount the corn used to fix carbon dioxide (CO_2). Furthermore, growing corn requires fossil inputs, among others, all of which were originally created with solar energy and thus are included in emergy analysis.
3. In the IMPACT 2002+ and Eco-indicator 99 methodologies, use of nonrenewable resources is included in the damage categories of resources, but renewable resources are omitted (Goedkoop and Spriensma 2001; Jolliet et al. 2003).
4. The Yanacocha mine is one of the largest gold mines (in terms of production) in the world. The mine produced 3.3275 million ounces in 2005 (Buenaventura Mining Company Inc. 2006). This represented more than 40% of Peruvian production (Peruvian Ministry of Energy and Mines 2006) and approximately 3.8% of the world's gold supply in 2005, if we assume 100% recovery of gold from doré and use the total of 2,467 tonnes reported by the World Gold Council (2006).
5. The system and inventory are described in detail in Supporting Information S2, Life Cycle Inventory of Gold Mined at Yanacocha, Peru.
6. "*x*E+*y*" is the form of scientific notation used throughout this document to represent "*x* times 10 to the *y* power."
7. For purposed of functionality in SimaPro, the integrity of the emergy algebra was not affected.
8. "Unit" processes as defined here correspond to the SimaPro definition, not to the unit processes defined earlier as one of the nine phases of mining.
9. Uncertainties for UEVs are shown in Supporting Information document S1 on the Web. The inventory uncertainty can be found in the inventory description in Supporting Information document S2.
10. The EYR may be defined as the total emergy in a product divided by the emergy in purchased inputs from outside the product system (Brown and Ulgiati 1997).
11. Sunlight on Peru = 5E+21 J = 5E+21 sej (Sweeney et al. 2008), because 1 sej = 1 J sunlight. 1.66E+21 sej in doré /5E+21 sej in average sunlight on Peru = 0.3.
12. This includes only the portion of direct electricity use from hydropower. Energy sources for all other inputs are assumed to be nonrenewable.
13. Emergy practitioners also point out that emergy of coproducts cannot be double-counted when the coproducts are inputs to the same system (see Sciubba and Ulgiati 2005, p. 1967). In LCA, however, all impacts have to be split according to one of the methods described in ISO 14044.
14. Resource depletion indicators are built into the most common LCIA methodologies, including TRACI and Eco-indicator 99 (Goedkoop and Spriensma 2001; Bare et al. 2003).
15. A detailed comparison between an inventory of this product and the inventory of gold at Yanacocha is presented in the Discussion section of Supporting Information S2 on the Web.
16. This implementation of CExD in SimaPro is incomplete and does not provide characterization factors for many of the chemicals used in the refining processes. The relative exergy contribution of chemicals to total exergy in gold would likely be higher if this were the case.

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Supporting Information

Supporting information may be found in the online version of this article:

Supporting Information S1: This supporting information contains a figure showing the process tree of environmental contribution (solar emjoules [sej]) to 1 gram (g) doré and three tables with uncertainty estimates. The first table provides uncertainty estimates for gold-silver bullion production, the second table addresses uncertainty in gold in the ground, and the third table addresses uncertainty in silver in the ground.

Supporting Information S2: This supporting information contains a life cycle inventory of gold mined at Yanacocha, Peru.

Please note: Wiley-Blackwell is not responsible for the content or functionality of any supporting information supplied by the authors. Any queries (other than missing material) should be directed to the corresponding author for the article.