Ecological and economical optima of material recycling

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ABSTRACT

The introduction of recycling technologies is often hampered by economical constraints and doubts over the environmental advantage of recycling schemes. Governmental agencies are interested in determining whether a recycling scheme really has environmental benefits and might be willing to distribute subsidies to economically help jump-start such schemes. In order to justify such subsidies it is helpful to demonstrate whether the scheme would be economically viable if full cost accounting would be applied.

Environmental Life Cycle Assessment methodologies suitable to assess a wide variety of recycling processes are outlined and applied to a case study of metal recycling from galvanizing sludge. Economical analysis and environmental life cycle assessments are performed to identify hidden burdens of primary material production. A range of possibilities to monetarise environmental damage potentials determined by environmental Life Cycle Assessment (LCA) are proposed and applied.

Investigated hidden costs are e.g. #) inferior workers health and security environments in many mining and refining sites, #) effects of deteriorating resource grades, #) resource production subsidies #) military expenses for resource production security, #) neglected long-term damages at mining sites from tailings. The sum total of externalities are found to be significant or even dominant compared to market prices. Including hidden costs, the comparison between primary material and recycling material is often found to shift considerably compared to micro-economical or simplified ecological assessments.

The proposed framework is able to compare recycling processes with primary material processes, with other recycling processes or with a mixture of both, and determine whether recycling is advantageous over competing options. It is also possible to determine whether there are thresholds of recycling efficiency regarding the environmental and/or economical advantage of recycling.

Life Cycle Assessments of recycling processes

Recycling schemes are often thought to be ecologically beneficial, and they often are. New recycling schemes need to demonstrate that they are indeed ecologically less damaging than current waste disposal options. Also there might be a limit to recycling rates, when very high recycling yields result in larger impacts than primary materials. Environmental Life Cycle Assessment (LCA) is a suitable tool to establish this. Recycling processes are often a challenge in LCA. They are often subject to controversial debate and difficult to handle due to their multi-functional characteristic of being a waste disposal service *and* a material production at the same time. In cases where only one of the two services is of interest, allocation methods need to be applied. If the *whole recycling process* is of interest, there is no need of allocation at all, since both characteristics – waste disposal and material production – are pertinent. It is therefore suggested, that for comparisons of (new) recycling schemes vs. established waste disposal options no allocation is done, but that all the considered options should be treated with the Utility Basket Method: A collection of functions shall be defined in such a way that all options can fulfil this palette or basket of functions. If a technology is not able to provide all desired functions, then common reference processes that supply those missing functions shall be added in suitable amounts.

In the case that recycling produces inferior material qualities (downcycling) then the recycling process shall be extended to include purifying processes that produce material qualities that can replace primary materials. If no such processes exist, the recyclate might be weigthed with its economical value. The use phase can change the composition of materials. The fate of impurities in waste materials shall be examined specifically and included if necessary.

The impossible but necessary monetarisation of Life Cycle Impacts

What does one case of child bronchitis cost? How much would we pay, to prevent it? How much would society pay to prevent cases of premature death? How much would we pay, to prevent a plant or animal species from extinction? And what if it is a mosquito species? It is hard or impossible to answer these questions, yet in order to compare visible, micro-economic prices of products with the hidden, external damages they cause, it is helpful to convert external damages, as established by LCA, into costs. We propose several procedures to establish a link between fully-aggregating Life Cycle Impact Assessment (LCIA) results and costs.

1) Damage costs of CO_2 and PM_{10} as established in [1],[2] are related to their characterisation factors
2) Damage costs of a disability adjusted life year (DALY) are related to other environmental damages (only for Eco-indicator'99 [3], [4]).
3) Damage costs of a country [5] are related to the national environmental damages as established by LCIA factors

From these procedures approximate ranges for the monetarisation of LCIA impacts are derived. The ranges of monetarisation of impact units of the LCIA methods Eco-indicator'99 (H,A), Umweltbelastungspunkte 1997 (aka BUWAL method, eco-points, ecological scarcity method, UBP'97), and a draft version of the new Umweltbelastungspunkte 2006 are shown in Table 1. The given ranges do not try to cover all possible values, but to give an estimate of the variability of monetarisation calculations.

Table 1: Approximate ranges of monetarisation of impact units for three LCIA methods

	Eco-indicator'99 (H,A) [4]	BUWAL eco-points '97 [6]	BUWAL eco-points '06 [7]
LCIA unit	points	UBP'97	UBP'06
	Monetarised impact in 2005 Swiss Francs (CHF_{2005})		
Small value	3.5	0.00015	0.0001
Mean value	10	0.00055	0.00035
Large value	40	0.001	0.0007

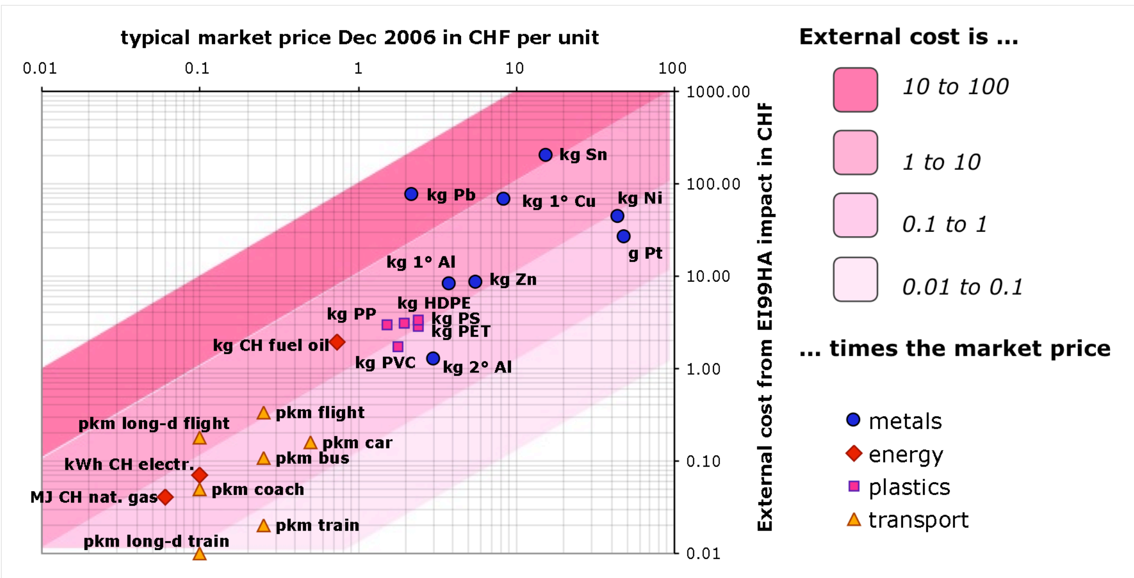

Figure 1: Current market prices (x axis) vs. results of mean monetarisation of environmental impacts according to Eco-indicator'99 (H,A) (y axis) for some products and services. The product units are given in the labels of the data points (MJ = megajoule, g = gram, pkm = person-kilometer).

The monetarisation can be applied to LCIA results and then represent the environmental part of external costs. A comparison of such external costs versus current market prices is shown for some existing life cycle inventories (LCI) in Figure 1. The results in Figure 1 suggest that external costs are often close or above current market prices. An internalization of such costs would lead to noticeable changes in production technology and consumption.

Apart from environmental costs, external costs also pertain to economical and social costs, e.g. resource production subsidies, military expenses for resource production security, or inferior workers health and security environments in many mining and refining sites, which are investigated in our study. However, with the exception of oil, we found that environmental cost calculations cover most of the externalities caused by resource extraction and production. Assessing environmental costs from LCA data can be incomplete, if the applied inventories are incomplete. Primary metal production produces large amounts of waste in ore processing (tailings), which are often unaccounted, but relevant. A first coarse estimate for damage from mining tailings sites was created, and included in the case study on galvanizing sludge recycling.

Case study: galvanizing sludge recycling

Galvanizing sludges are the residues from galvanising processes (surface metallization). These sludges are often landfilled, or stored in German underground deposits (old salt mines). Since they contain high concentrations of metals, galvanizing sludges are frequently recycled in smelters of hydrometallurgical operations for their metal content.

This case study should establish if there are boundaries to the metal content that a galvanizing sludge should contain in order to be ecologically less damaging than the non-recycling landfilling option. Of the various valuable metals in galvanising sludge only copper, nickel, zinc, and lead were considered as recyclates, merely for reasons of practicability and scope.

For the recycling process, four smelter models for the target metals were created, that allow the calculation of air and water emissions specific to the waste feed, i.e. cadmium emissions to air are proportional to the cadmium content in the recycled sludge. Smelter residues can sometimes be fed into other smelters. For example the collected flue gas dust from a zinc smelter is usually rich in lead, and can be recycled in a lead smelter. Such cross-connections are included in the model. Thus, for example if galvanising sludge is fed to a copper smelter, the ensuing cascade of smelters produces secondary copper plus some zinc and lead, but no nickel.

The functional unit comprises the disposal of one kilogram of galvanising sludge (disposal function), the production of a certain amount of metals (35 g copper, 35 g nickel, 14 g zinc, 94 g lead, based on maximal contents in sludge) and the production of inert material, which can be used as abrasive or building material (560 g). This is the Utility Basket, as introduced above. In the case of landfilling, only the disposal function is fulfilled, and the other functions need to be added in this option: metals are taken from primary metal sources, inert material is added as corundum abrasive.

Landfilling is assessed with waste-specific leachate emissions, using the landfill models created in [8]. LCI data is taken or derived from the ecoinvent database [9] or own studies. Primary metal production was augmented with new data on ore processing waste (tailings) and smelter slag disposal. As LCIA methods Eco-indicator'99 (H,A), UBP'97, UBP'06, and Human Toxicity Potential 500yr from CML'01 [10] were chosen.

Figure 2 shows a typical result of this assessment. Recycling is less burdening than landfilling regardless of the zinc content. Even for a hypothetical *zero* zinc content, recycling would be superior, since prior to recycling the sludge is dried, which reduces the landfilled volume, as where in landfilling sludge is solidified with cement and thus occupies a larger volume. The burden for recycling *decreases* with increasing zinc content, because increasing amounts of secondary zinc are produced. This reduces the amount of added primary zinc necessary to arrive at the metal amounts required by the Utility Basket. The majority of the burdens in both options originate from the added primary metals, especially copper. The burdens from the recycling process itself (transport, drying, smelting, hydrometallurgy) are minor in comparison. Thus the fact that metals are discarded, removed from the technosphere and put to disuse is ecologically more relevant in this example than the burdens originating from either the recycling or landfilling processes. If a less burdening type of disposal is chosen (underground salt mine storage with no leachate emissions) the disposal option burdens can fall below the burdens from recycling, depending on the LCIA method and the recycled metal.

Within the primary metal burdens the newly added inventories for *tailings* waste make up a considerable part of the burdens. Depending on the metal and the LCIA method, tailings contribute typically between 20% and 80% of the total burden. Thus lack of assessing burdens from tailings – which unfortunately is quite common – runs the risk of overlooking relevant, or even dominant, burdens in the primary metal production chain. The data created in this study is currently (May 2007) in progress of being included in the ecoinvent LCI database v2.0.

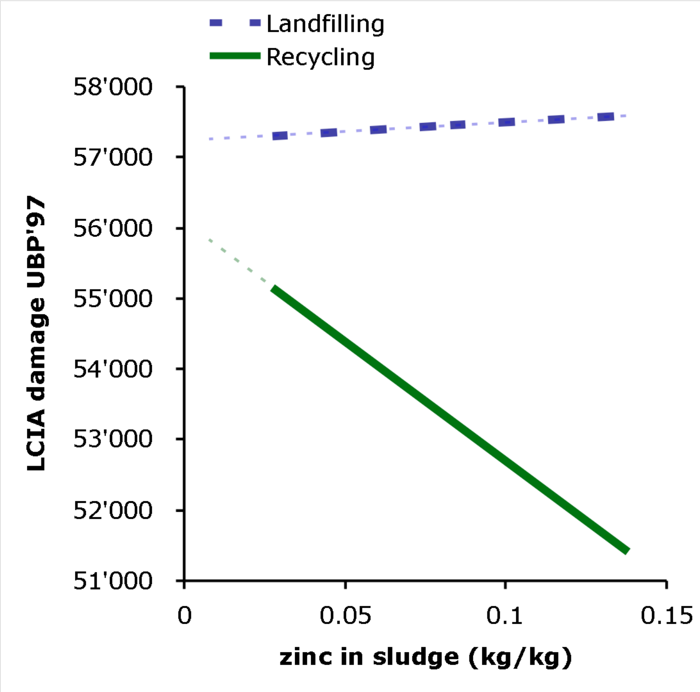

Figure 2: LCA results for disposal and recycling of galvanising sludge with variable zinc content.

Results for variation of other metals and/or other LCIA methods give similar results. Recycling is found to be less burdening in all cases. The LCA result for landfilling in Figure 2 (blue line) is slightly *increasing* with increasing zinc content. This is the effect of applying waste-specific landfill models, which heed the specific composition of the landfilled waste. The increasing burden witnesses the fact that in this option more zinc is being landfilled and leached into the environment. This effect is especially prominent with varying copper content, as copper emissions have large characterisation factors. Thus it can be concluded that recycling of galvanising sludge is less burdening over landfilling regardless of metal content.

The current recycling fees of galvanising sludges are very variable across recyclers and depend on the recycled metal and the sludge composition. Gold sludges are recycled for very small fees basically covering transport costs. Nickel recyclers sometimes offer a sliding scale depending on nickel content in sludge. Typical recycling fees are in the proximity of 150 – 300 CHF per metric ton. Landfilling or salt mine storage fees are approximately 300 – 600 CHF per metric ton. In a micro-economical view recycling is therefore usually the preferred option. Being able to monetarise the environmental advantage of recycling galvanising sludge over landfilling is helpful in order to determine which additional costs can be justified to be placed upon the industry in those cases where recycling is more expensive than disposal. The monetarised environmental advantage of recycling is the difference of environmental costs caused by disposal and the costs caused by recycling. In the average case the advantage of sludge recycling is in the range of 2000 CHF to 20'000 CHF per metric ton, with a median value of 5000 CHF/ton, depending on the recycled metal and the monetarisation approach (Table 1). Thus, in cases where it is necessary to promote sludge recycling over disposal *very large* additional costs on disposal can be justified.

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