Perspective

How to define the quality of materials in a circular economy?

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ABSTRACT

Improving the circularity of our economy calls for easily quantifiable metrics that allow us to track our progress towards circularity. We propose the use of a material quality indicator based on the energy use of recycled products versus their counterparts produced from primary material inputs only. We argue that such an indicator can cover at least the environmental dimension of the circular economy in a sufficient way and is therefore useful for the assessment of the circularity of our economy.

The quality of materials is important for defining the circularity of the economy (Nakamura et al., 2017), but is so far neglected in circular economy policies (McDowell et al., 2017). Here we focus on two important qualitative aspects of recycling: the quality of the recycled material and the functionality of substances present in materials. The quality of the recycled material may well be different from, often lower than, the quality of the primary material. We will take this aspect into account by considering the production of a material with the same quality as the recycled material from primary inputs.

The functionality of substances present in materials is relevant to downcycling and the consideration of functionality is in line with the argument that conservation of functionality 'as long as possible' is important for a circular economy (Iacovidou et al., 2017). Two matters are important in the context of functionality: (1) the loss of functional substances present in the primary material and (2) counteracting the emergence of dysfunctional substances in the recovered product. The loss of functionality of substances present in the primary material may occur when such substances partition to production residues. For instance, in the case of recycling steel by re-melting, the percentage lost to slags of functional alloying elements such as Mn, Nb and V may well exceed the percentage of functional Fe lost to slags. Loss of functionality may also occur when substances have functionality in the primary product but not in the secondary product. For instance, Ni and Cr are functional in stainless steel, but when stainless steel is used as an input in recycling to carbon steel, Ni and Cr lose their functionality (Nakamura et al., 2017). Rather than allocating a zero energy value to non-functional elements in an alloy like in Nakamura et al. (2017), we compare the recycling of a material to an alternative production route

for a material with the same quality as the recycled material which uses only primary materials inputs. In this approach the energy invested in alloying elements that are non-functional in the secondary material is not completely lost. This is considered justified because these elements still contribute to the mass of the secondary material.

Counteracting the emergence of dysfunctional substances in the recycled product regards the presence of substances which, due to their relatively high concentration, negatively affect product characteristics. One example thereof is the presence of too much ink in recycled paper used for printing. This can be counteracted by de-inking inputs of printed paper in paper recycling. This exemplifies cleaning. A second example concerns the presence of Cu in shredded steel. When the amount of Cu in scrap used in secondary steel production is in excess of the amount following from meeting steel quality requirements (tolerance), reducing the concentration of Cu in recycled steel is possible by dilution with primary product.

Taking into account the quality of the recycled product, the functionality of substances and the mass balance, we propose the following indicator for the circularity of material quality (Q_c), where the numerator expresses the net energy savings due to recycling primary material (MJ/kg) and the denominator is the embodied energy of 1 kg of primary material (MJ/kg):

$$Q_c = \frac{\alpha \cdot (E_{prod,s} - E_{r,s}) - E_{c,s} - \beta \cdot E_{d,s}}{E_p} \quad (1)$$

where:

α = the amount in kg of secondary material that can be made from recycling 1 kg of primary material. Note that α is < 1 if there are losses

Table 1
Parameters used for calculating the energy circularity of steel.

Steel	Energy	Details
α	1.51	Due to losses 1.105 kg scrap is required for 1 kg of usable scrap, the scrap input (by mass) is 60%. α = 1/(1.105*0.6) = 1.51
β	2/3	Dilution is done by mixing 40% pig iron with 60% scrap, so β = 2/3
$E_{prod,s}$	24.4 MJ	1 kg Steel low-alloyed, steel production, converter
$E_{r,s}$	9.1 MJ	Energy for recycling including scrap sorting and pressing 1 kg Steel, low-alloyed, RER, steel production, electric arc
$E_{c,s}$	0	No cleaning inputs (sorting and pressing are included under $E_{r,s}$)
$E_{d,s}$	16	1 kg Pig Iron, GLO, market for pig iron
E_p	62.8 MJ	1 kg Chromium steel 18/8, steel production, converter
Q_C (Eq. (1))	**0.198**	$\frac{\alpha \cdot (E_{prod,s} - E_{r,s}) - E_{c,s} - \beta \cdot E_{d,s}}{E_p}$

Data from Ecoinvent database: Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B. 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21(9): 1218–1230.

and no extra primary material input is required, while α > 1 if relatively large amounts of primary materials need to be added for dilution (dimensionless).

β = the ratio of diluting material to primary material to be recycled. (dimensionless).

$E_{prod,s}$ = the cradle-to-gate life cycle energy (in MJ/kg) required for producing material with the same quality as the secondary material from primary inputs (i.e. without the use of recycled materials) (in MJ/kg).

$E_{r,s}$ = the direct cradle-to-gate life cycle energy requirement for producing the secondary material from material that is to be recycled (in MJ/kg).

$E_{c,s}$ = the energy required for cleaning (can include pre-processing, pre-treatment and sorting) the material inputs per kg primary material to be recycled (in MJ/kg).

$E_{d,s}$ = the embodied cradle-to-gate life cycle energy in the primary materials required for dilution, necessary to obtain secondary material of sufficient quality (in MJ/kg).

E_p = the cradle-to-gate life cycle energy required for producing 1 kg of primary material (in MJ/kg).

To give a quantitative indication of what application of Qe means in the case of stainless steel recycling, we have selected as primary material chromium steel 18/8, which is a stainless steel with minimum mass-based Cr and Ni contents of 18% and 8% respectively. After its' use as stainless steel, the chromium steel is recycled to carbon or low-alloyed steel in which Cr and Ni have no function (e.g. Nakamura et al., 2017). In this example it is assumed that the recycled material is mixed with metal from other sources, contaminating the scrap with Cu. Therefore the addition of primary pig iron is necessary to reduce the Cu concentration. 60% of the inputs by mass is from recycled material while 40% of the inputs come from primary pig iron. Under these assumptions the energy circularity of recycling stainless steel to low-alloyed steel is 0.198 (Table 1).

The indicator for the circularity of materials we have proposed here is based on energy demand. Energy demand is an important indicator of environmental impact and reducing the primary energy demand of a product is likely to decrease its overall environmental impact (Steinmann et al., 2017). Iacovidou et al. (2017), however, argued that circularity-indicators covering a single domain of value often deliver misleading messages. They favor multidimensional circularity indicators that also include technical, economic and social dimensions. Would practitioners and policy makers consider themselves adequately informed by an energy-based indicator that mainly covers the environmental domain of the circular economy? This may be doubted, as can be illustrated by the example of using recycled aluminium alloys in cars. Modaresi et al. (2014) have pointed out that car producers require that safety relevant car components such as wheels should be made from primary alloys. Such an example demonstrates that a single indicator is unlikely to be sufficient in the broader context of the circular economy. Nevertheless, energy use in an important matter in the environmental domain of the circular economy. In combination with other, such as economic and legal aspects, the material quality indicator proposed here can help to better quantify the circularity of the economy.

References

Iacovidou, E., Velis, C.A., Purnell, P., Zwirner, O., Brown, A., Hahladakis, J., Hopkins, J.M., Williams, P.T., 2017. Metrics for optimizing the multi-dimensional value of resources recovered from waste in a circular economy: a critical review. J. Clean. Prod. 166, 910–938.

McDowell, W., Geng, Y., Huang, B., Bartekova, E., Bleischwitz, R., Türkeli, S., Kemp, R., Doménech, T., 2017. Circular economy policies in China and Europe. J. Ind. Ecol. 21 (3), 651–661.

Modaresi, R., Lovik, A.N., Müller, D.B., 2014. Component- and alloy-specific modeling for evaluating aluminum recycling strategies. Environ. Sci. Technol. 46, 8587–8594.

Nakamura, S., Kondo, Y., Nakajima, K., Ohno, H., Pauliuk, S., 2017. Quantifying recycling and losses of Cr and Ni in steel throughout multiple life cycles using MaTrace-alloy. Environ. Sci. Technol. 51, 9469–9476.

Steinmann, Z., Schipper, A., Hauck, M., Giljum, S., Wernet, G., Huijbregts, M., 2017. Resource footprints are good proxies of environmental damage. Environ. Sci. Technol. 51 (11), 6360–6366.