

ENERGY FLOWS ALONG THE PRODUCTION AND USE OF SECONDARY MATERIALS WITH A SPECIAL FOCUS ON CONCRETE

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ABSTRACT. Urban mining in the existing building stock can contribute to securing raw materials and conserving natural resources if the potential of recycling construction waste is consistently exploited. From an ecological point of view, it is on the one hand interesting what amounts of primary materials can potentially be substituted and on the other how much energy need to be invested for this. At present, the recycling of construction waste usually is considered from a material perspective. There is lack of an approach, extending material-oriented considerations by energetic aspects. The aim is to develop a uniform research approach by which energy expenditure during recycling of important construction products can be determined. Besides concrete seven further construction products are investigated. Recycling paths are described and analysed along waste management processing steps taking into account the quality of the demolition materials and the quality requirements of the possible new application variants in the construction sector. The result is a clear plea for more consistent recycling. The analyses of concrete indicate that "high-quality" recycling only results in energy advantages when "high-grade" demolition material is used. However, so-called "down-cycling" solutions allow resource conservation to be combined with energy savings, even with lower-quality demolition materials. The single-minded focus on "high-quality" recycling according to the general understanding should therefore be questioned. Instead, preference should be given to solutions that take resource conservation into account in a more holistic way especially with regard to resource conservation and climate protection.

KEYWORDS: Circular economy, energy consumption, recycling, resource efficiency.

1. INTRODUCTION

The recycling of construction waste can make an important contribution to climate and nature protection, but above all to the conservation of resources. In Germany, the German Resource Efficiency Programme formulated the goals of decoupling resource consumption from economic growth, doubling raw material productivity by 2020, reducing the environmental impacts associated with the use of natural resources as far as possible and further developing and expanding the circular economy [1]. In order to enable almost circular economic activity in the construction sector, the corresponding demolition materials must be recyclable and be available with a certain consistency in specific quantities.

Resource conservation potentials using secondary materials expressed in tonnes of material are known for some selected construction products [2, 3]. However, an assessment of the resource conservation potentials only on the basis of these material figures is too one-sided, as energy aspects are not taken into account. There are individual studies that focus on specific construction products with regard to the energy used in recycling [4]. However, there is no comprehensive overview for all important construction products. There is a lack of a common approach by which im-

portant construction products can be presented synoptically and compared to each other in terms of their energy expenditures during recycling.

The aim of the present study was to extend the material-oriented studies on resource conservation potentials to include energy considerations and to develop a uniform approach by which important construction products can be presented and compared in a synoptic way with regard to their energy expenditure during recycling [5]. The following questions should be clarified: Which energy expenditures are associated with recycling? What is the energy expenditure of recycling compared to the energy expenditure of standard production without recycling? Are there energetic differences between "high-quality" application variants (in building construction) and less "high-quality" application variants (in civil engineering and landscaping)?

The investigations focused on eight construction products: concrete, bricks, sand-lime bricks, gypsum, flat glass, mineral (stone) wool, PVC profiles, and PVC floor covering. For all of these, we energetically investigated the paths from demolition material to a new application variant in building construction, civil engineering or landscaping. This we did taking into account the quality of the demolition material and the quality requirements of the new application

Process chain	demolition material	secondary material	application variant
Concrete	pc 1	concrete without coarse adhesions	recycled aggregates 2/16 type 1 concrete foundation C20/25
	pc 2	broken concrete mixture	recycled aggregates 2/22 type 2
	pc 3	(with brick, limestone, plaster)	recycled aggregates 0/32 for road construction ballast base layer for roads

TABLE 1. Model-like pc for concrete.

variant in the construction sector.

2. METHODOLOGY

In order to carry out these investigations, we have developed an analytical approach which generally regulates the methodological procedure, following the idea of a continuous Material Flow Analysis as described in [6].

2.1. BALANCE FRAMEWORK AND TERMS & DEFINITIONS

Starting point of the considerations are demolition materials. Demolition materials are quantities that are available in a certain quality after the demolition of a building (e.g. broken concrete without coarse adhesion). These materials come exclusively from building construction. Construction site waste is not included in the analysis. In order to be able to supply demolition materials as secondary materials and substitute materials for a new application variant, they must be prepared accordingly. A new application variant is the use of demolition materials for a new purpose and location (e.g. broken concrete as aggregates for foundation concrete).

All necessary preparation and further processing steps depend on the quality of the demolition material itself as well as the quality requirements of the new application variant. In order to take these dependencies into account, there is a need to consider the entire process from the demolition material to the new application variant. This is applied in the form of characteristic model-like process chains (pc).

Due to the large variety of possible process chains (large variety of possible deconstruction qualities, types of processing, further processing methods, application variants) two to three demolition materials and two to three typical application variants were combined into model-like pc for each construction product. The pc are defined in consultation with experts from the relevant construction product associations in Germany. Table 1 shows the pc for the example concrete.

On the way from the demolition material to the new application variant, a secondary material is first created and in a further step a substitute. The terms "secondary material" and "substitute" are described

more in detail in the standard DIN EN 15804:2014-07 [7] (Table 2).

With regard to DIN EN 15804:2014-07, the selected balance framework starts at the end of the waste treatment step of the preceding product system "building". Processes before the end of the waste property stage (such as collection and transport) are part of the waste treatment of the above product system "building". In contrast, processes that are required after the end of waste property stage to allow primary materials to be replaced in another product system are considered to be outside the above system "building" (see [7], para. 6.3.4.5 Note 3). These regulations are complied with here. The analyses start with the demolition material at the recycling company and integrate all preparation steps for the production of the secondary material as well as its further processing up to the substitute (preceding demolition technology, collection processes, sorting processes and transports on the site are not considered).

2.2. 3-STEP ANALYSIS APPROACH OF PROCESS CHAINS

The energetic analyses of the model-like pc of the different construction products follow a uniform methodical approach. It is divided into three steps:

1. Determination of the energy required to process a demolition material into a secondary material.
2. Determination of the energy expenditure for the further processing of the secondary material into a substitute that can replace a primary material in a functionally equivalent way, using energy additions/deductions.
3. Comparison of the energy expenditure for the substitute with that for the primary material to be replaced (Figure 1).

The steps of the methodical procedure are explained more in detail in the following paragraphs using concrete as example (pc 1: from pure crushed concrete to recycled aggregate for foundation concrete C20/25, Table 1).

2.2.1. ENERGY EXPENDITURE FOR PROCESSING SECONDARY MATERIAL

Here the energy required to process the demolition material into secondary material is calculated

Term	description of important terms
Secondary material	According to DIN EN 15804:2014-07 [7], para 3.29, a secondary material is <ul style="list-style-type: none"> - any form of material recovered from a previous use or from waste and replacing a primary material, - recorded at the point at which the secondary material enters the system from another system, - recovered from a previous use or from waste from a product system and used as input to another product system.
Substitute	Substitutes are "secondary materials having left the system for primary material production [and are declared] in Module D if they have functional equivalence to the replaced primary material" ([7], para 6.3.4.5, note 3).

TABLE 2. Description of the terms "secondary material" and "substitute" according to DIN EN 15804:2014-07.

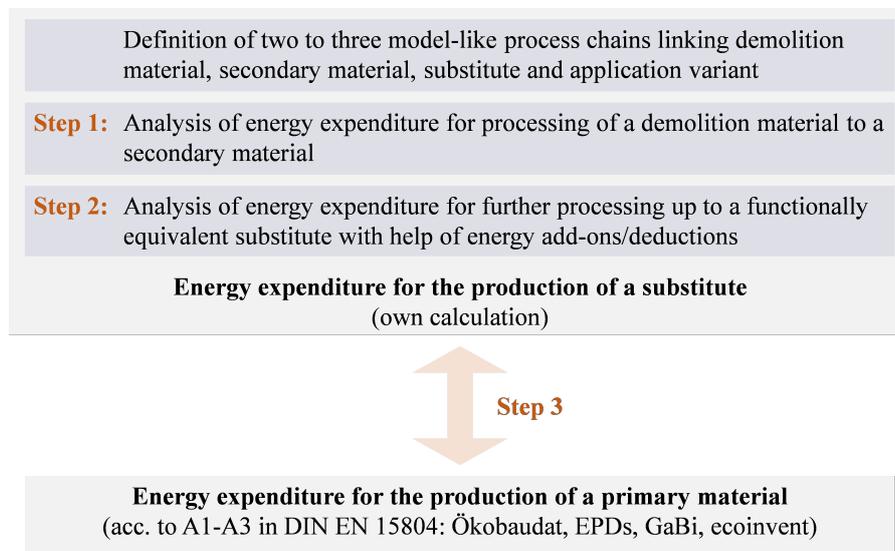


FIGURE 1. Methodical procedure.

in MJ/kg. The following list shows which analysis and calculation steps are required to determine the average energy expenditure.

- Identification and definition of characteristic main processing steps to produce the secondary material (e.g. pre-screening, crushing, metal deposition etc.).
 - Definition of technical components/machinery for the identified processing steps (e.g. sieve, jaw crusher, magnetic separator etc.).
 - Determination of average energy expenditures for the defined components/machinery (e.g. sieve 0.0021 MJ/kg, jaw crusher 0.0022 MJ/kg, magnetic separator 0.0147 MJ/kg etc.).
 - Calculation of the energy required to produce the secondary material by adding the energy values of the identified process steps and defined machines (e.g. 0.036 MJ/kg for all steps).
 - Analysis of the material flows and calculation of the proportions for target product, co-products and waste. For pc 1 of concrete this is 48% target product (recycled aggregate 2/16 type 1), 43% co-products (crushed concrete 16/22, 22/32, 32/56, 56/x and Sand 0/1, 0/2) and 9% waste (pre-screen material 0/8 and impurities/foreign substances). For co-products there is the possibility of further use. They receive an energy allocation. There is no further use for waste and therefore no energy allocation.
 - Calculation of the energy allocation for the co-products based on the material flow proportions (e.g. 0.013 MJ/kg for crushed concrete > 16 mm and sand ≤ 2 mm).
 - Calculation of the energy required to produce the secondary material considering the energy allocations for co-products (e.g. 0.036 MJ/kg – 0.013 MJ/kg = 0.024 MJ/kg)
- In sum step 1 ends with the energy expenditure for processing the secondary material.

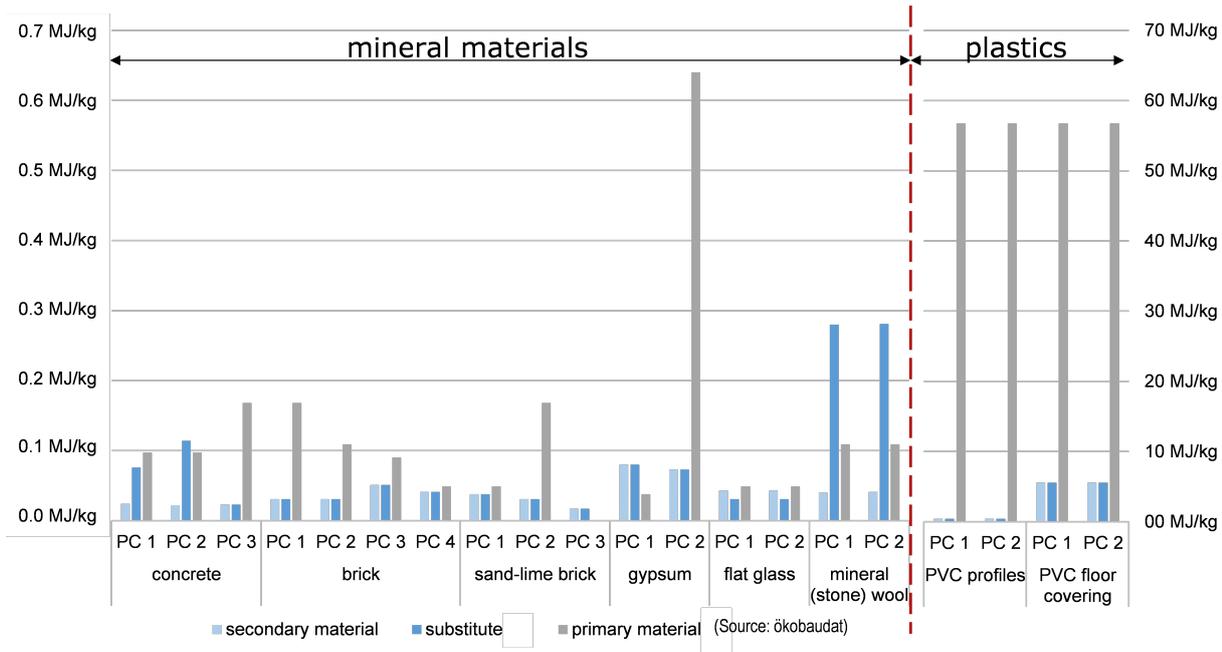


FIGURE 2. Energy expenditures of the selected construction products - a comparison.

2.2.2. ENERGY EXPENDITURES FOR FURTHER PROCESSING UP TO A SUBSTITUTE

Here it is analysed which energy expenditure is connected with the further processing of the secondary material to the substitute. Methodologically, all necessary measures and processes are analysed and the differences between the production process with recycled material and the standard production process without recycling are worked out. The differences can be associated with both additional and reduced energy expenditure. This means that the previous energy expenditure for the secondary material (0.024 MJ/kg) receives an energy add-on or an energy deduction. Additional and reduced energy expenditure result mainly from modified recipes and modified process steps¹. Modified recipes are, for example, different mixing ratios or additional admixtures of auxiliary materials. Modified process steps can be additional, shortened or unnecessary process steps. In the case of concrete, it is above all necessary to increase the cement content in the recipe (+ 1%). Modified process steps are not necessary ($\pm 0\%$). This results in a total energy add-on of + 0.052 MJ/kg. In total, this results in the energy expenditure for the substitute (0.076 MJ/kg).

2.2.3. COMPARISON OF THE ENERGY EXPENDITURE FOR THE SUBSTITUTE WITH THAT OF THE PRIMARY MATERIAL

Finally, the production of construction products without recycled material is compared in terms of energy to that with recycled material. This is done

¹Modified transport efforts also lead to additional or reduced energy expenditure. However, they could not be calculated due to the poor availability of data. There is a need for research.

at the level of the material to be replaced or the material to be substituted. In this way, the energy expenditure of the substitute is compared with that of the primary material. This comparison allows assessments to be made as to whether recycling makes sense from an energy perspective. The energy characteristics of the primary materials are taken from the source ökobaudat [8] and DIN EN 15804 compliant secondary sources [9], [10], [11].

3. RESULTS

Following the methodological procedure presented, energy expenditure for all pc of the selected construction products was calculated for the production of secondary materials and further processing up to the substitutes and compared with the energy expenditures of primary materials (to be replaced) (Figure 2).

In general, the results show that under the given framework there is almost nothing to prevent recycling. The energy expenditure for the secondary material and the substitute is usually lower than the energy expenditure for the primary material. Exceptions are mineral wool and one pc of concrete (pc 2) and one of gypsum (pc 1).

For mineral materials, recycling is not associated with excessive energy expenditures and makes sense above all with regard to the mass aspect, as recycling reduces the extraction of raw materials and protects the natural environment and landscape. For plastics the energy aspect is more significant.

A specially look at concrete shows that the quality of the demolition material as well as the material requirements of the new application variant have a significant influence on the energy expenditures for recycling (Table 3). As a rule, the prin-

Construction product concrete	pc 1	pc 2	pc 3
Demolition material	concrete without coarse adhesions	broken concrete mixture (with brick, limestone, plaster)	
ee of all processing steps	0.036 MJ/kg	0.031 MJ/kg	0.025 MJ/kg
discharge co-products	43%	34%	10%
energy allocation (ea) co-products	0.012 MJ/kg	0.009 MJ/kg	0.002 MJ/kg
Secondary material	recycled aggregates (ra) 2/16 type 1	recycled aggregates (ra) 2/22 type 2	ra 0/32 for road construction
ee of all processing steps with ea	0.024 MJ/kg	0.022 MJ/kg	0.023 MJ/kg
Substitute			
modified recipes	+ 0.052 MJ/kg	+ 0.092 MJ/kg	± 0 MJ/kg
modified process steps	± 0 MJ/kg	± 0 MJ/kg	± 0 MJ/kg
ee with add-ons/deductions for modification	0.076 MJ/kg (77%)	0.114 MJ/kg (118%)	0.023 MJ/kg (14%)
Primary material	aggregate of gravel (2/32; 80%) and chippings (2/15; 20%)	aggregate of gravel (2/32; 80%) and chippings (2/15; 20%)	aggregate of gravel round (4/x; 50%) and gravel broken (4/x; 50%)
ee for processing primary material ¹	0.097 ² MJ/kg (100%)	0.097 ² MJ/kg (100%)	0.168 MJ/kg (100%)
Application variant	concrete foundation C20/25		crushed stone sub-base (roads)

¹ Source: ökobaudat [8].

² Using ecoinvent [9] results in a different figure: 0.057 MJ/kg. This also influences the figure of the substitute due to the recipe.

TABLE 3. Energy expenditure (ee) calculations of the different pc of concrete.

ciple applies that "high-quality" demolition material (clean/without adhesions) is usually associated with a "high-quality" application variant (building construction) and a "low-quality" (unclean/ with adhesions) one with a "low-quality" application variant (civil engineering/landscaping).

However, one and the same demolition material can also be used in different application variants (pc 2 and 3). For example, the demolition material crushed concrete mix can be used both as aggregates for the production of foundation concrete (pc 2) and as a ballast base layer in road construction (pc 3). The first variant has higher quality requirements and is also associated with higher energy expenditure. These result from a different secondary material: recycled aggregates 2/16 type 1 for concrete foundation (pc 2) and recycled aggregates 0/32 for road construction (pc 3). In addition, energy-relevant recipe adjustments (e.g. modified ratios for superplasticizer, water or cement) are required (pc 2) to produce a substitute equivalent to the primary material. A higher cement ratio content in particular has an impact on energy expenditure. Compared to the two pc, the crushed stone sub-base for road is thus the energetically bet-

ter application variant.

Likewise, two different demolition materials can have one and the same use (pc 1 and 2). In this way, both broken concrete without adhesions (pc 1) and crushed concrete mix (pc 2) can be used for the production of foundation concrete. Here, however, the "low-quality" demolition material (crushed concrete mix) is the less efficient variant in terms of energy. It is true that the production of aggregates 2/22 type 2 requires less energy than that of aggregates 2/16 type 1. However, changes in the recipe finally lead to a higher energy expenditure. In comparison of the two process chains, the broken concrete without adhesions is therefore the more energy-efficient starting demolition material.

The examples for concrete show that the use of recycling material in building construction can lead to different energy results with different types of demolition material (pure concrete or concrete mix). For example, the energy expenditure for the substitute in pc 1 is approx. 20% lower and in pc 2 approx. 20% higher than the energy expenditure for the primary material to be replaced (aggregates for concrete foundation). In contrast, energy savings of approx. 85%

are possible in road construction if recycled aggregates are used instead of primary aggregates (pc 3). If these results are taken into account, both "high-quality" and "lower-quality" recycling should be given attention in the interests of resource and climate protection.

4. SUMMARY AND CONCLUSIONS

In line with the objectives we developed a standard uniform balance approach to assess energy expenditure. Using this approach we calculated two to three pc for each of the selected construction products and provided a first set of energetic figures for recycling.

The analyses show that recycling is worthwhile. Compared to the use of primary materials, it is generally not associated with an excessive use of energy. However, there are some exceptions. Every building product has its own specific quality requirements and must be considered individually. For mineral materials, recycling makes sense above all with regard to the mass aspect, as recycling reduces the extraction of raw materials and protects the natural environment and landscape. For plastics the energy aspect is more significant.

It also becomes clear that the pc of the construction products have to be considered from the demolition material until the new application variant is reached. This is because each new application variant is associated with certain quality requirements for the secondary material up to the substitute, which finally affect the energy expenditure.

In summary, the analyses of concrete show that "high-quality" recycling (building construction application) only brings energetic advantages if "high-quality" demolition material (pure concrete breakage) is used. "Low-quality" recycling (road work application) on the other hand allow resource conservation to be combined with energy savings, even with lower-quality demolition materials. The single-minded focus on "high-quality recycling" according to the general understanding should therefore be questioned. Instead, preference should be given to solutions that take resource conservation into account in a more holistic way especially with regard to resource conservation and climate protection. In order to be able to assess this comprehensively, it is always necessary to look at the entire process chain, starting with the construction waste and its quality, the intended recycling product and the intermediate treatment and processing steps. This should not stop at today's common technologies. Rather, it is important to keep an eye on innovative technical developments. For example, the use of geopolymers as cement substitutes can lead to a significant reduction in greenhouse gas emissions [12] and thus have an impact on the advantages of the recycling processes under consideration.

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