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Life cycle assessment of post-demolition autoclaved aerated concrete (AAC) recycling options

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ABSTRACT

Autoclaved aerated concrete (AAC) is a widely used building material for masonry units, prefabricated reinforced components, and lightweight mineral insulation boards. Its low thermal conductivity and good fire resistance increase its popularity in residential buildings. Thus, post-demolition wastes are expected to increase in the future. However, post-demolition AAC (pd-AAC) is mainly disposed in landfills while landfill capacities decrease and legal framework conditions in Europe are tightening. This study performed life cycle assessments (LCA) of different pd-AAC recycling options and compared them to each other and to current landfilling to identify the best end-of-life handling of pd-AAC from an ecological perspective. The functional unit was 1 kg pd-AAC, and the system boundaries included pd-AAC at the demolition site, transports, pd-AAC treatment, and secondary production processes. Final products of the recycling process gained environmental credits/rewards for avoiding primary production using system expansion. Providing primary resources, primary production, and use phase were not in the scope of this study. Results show that especially closed-loop recycling of pd-AAC in AAC production has a high potential of improving environmental impacts. In the best recycling option (high substitution in AAC-0.35), potential savings per kg pd-AAC compared to landfilling reach up to 0.5 kg CO_2-Eq, 7 MJ fossil resources, 0.005 mol $H+$-Eq (acidification), 0.17 CTU (freshwater ecotoxicity), 0.2 g P-Eq (freshwater eutrophication), 5.2×10^{-9} CTUh (carcinogenic effects), 4.4×10^{-8} CTUh (non-carcinogenic effects), 2.5×10^{-5} g CFC-11-Eq (ozone layer depletion), and 1.6 g NMVOC-Eq (photochemical ozone creation). Despite data uncertainties, recycling of pd-AAC is advantageous for several recycling options, including the production of AAC, light mortar, lightweight aggregate concrete, and shuttering blocks made from concrete without fine fractions (no-fines concrete). In Germany, up to 280,000 t CO_2-Eq could have been saved in 2022 by pd-AAC recycling using different recycling options instead of landfilling.

1. Introduction

The construction and demolition (C&D) sector is associated with large shares of global greenhouse gas (GHG) emissions and resource consumption. In 2012, construction and demolition waste (C&DW) exceeded 3 billion tons worldwide (Akhtar and Sarmah, 2018), and the global concrete production used between 25.9 and 29.6 billion tons of aggregates (Peduzzi, 2014). In the future, "the pressure on natural resources will increase, while new infrastructure, services, and housing will be needed" due to a rising world population (OECD, 2020). Therefore, reaching the UN sustainable development goals, particularly sustainable cities, responsible consumption and production, and climate action (UN, 2020), will not be possible without the C&D sector. C&DW recycling is a promising approach to preserving natural deposits of sand, gravel, lime, and other construction materials and reducing GHG emissions. However, "the potential of the circular economy to support sustainable cities, regions, and countries still needs to be unlocked" (OECD, 2020) as inappropriate design-for-recycling, ineffective collection/sorting and immature recycling technologies hamper an effective circularity of building materials. The European waste and recycling regulation (European Parliament and Council, 2008) stipulates C&DW recycling rates of 70% and requires fulfilment of Regulation No 305/2011 (European Parliament and Council, 2011) for products with recycled content.

Abbreviations: pd-AAC, post-demolition autoclaved aerated concrete; AAC, autoclaved aerated concrete.

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Autoclaved aerated concrete (AAC) is made of quartz sand, cement, quicklime, anhydrite or gypsum, aluminium powder/paste (as aerating agent), and water (Kreft, 2017; German Institute for Standardization, 2018). During production, a porous structure typical for AAC is formed where the millimetres to nanometres sized pores make up 60 – 85 vol.-% (Anders, 2018). AAC has a low density and excellent thermal insulation properties that outperform other materials like classical clay bricks, calcium silicate units, or concrete. Annually, 16 million m^3 AAC is produced in Europe (EAACA, 2020) and 11.6 million m^3 (2017) in Russia (Grinfel'd et al., 2018). Globally, a production capacity of 450 million m^3 for non-reinforced AAC blocks is prevalent (Fouad and Schoch, 2018). For Germany, an annual post-demolition AAC (pd-AAC) volume of 1.4 million m^3 in 2022 and a sharp increase to more than 4 million m^3 in 2050 is expected (Steins et al., 2021).

Usually, post-demolition mineral construction materials are downcycled and used in road construction, earthworks, civil engineering, concrete production, and landscaping (Knappe et al., 2012). However, pd-AAC cannot be recycled in the applications mentioned above due to adhering substances (Deilmann et al., 2014), porous structure, and sulphate content. Besides, AAC has a relatively low compressive strength, preventing recycling in load-bearing components. Thus, pd-AAC is mainly backfilled or landfilled. But, landfilling capacities are limited, and landfill fees are expected to rise, especially in densely populated areas (Riegler-Floors and Hillebrandt, 2018; Knappe et al., 2012).

Unlike freshly produced AAC, crushing of pd-AAC (Section 2) results in more AAC powder (approximately 75%) than granulate (approximately 25%) (practical trials[1]; (Gyurkó et al., 2019)). While pd-AAC granulate retains the porous AAC structure, pd-AAC powder does not. If sufficient purity is given, the granulate could be used for different purposes, e.g. oil binder and animal bedding, as it is already done today with granulate from freshly produced AAC. In contrast, only limited applications for pd-AAC powder are available. Therefore, high-quality recycling options, particularly for pd-AAC powder, are needed.

Currently, direct reuse of pd-AAC blocks is not feasible in practice due to high costs resulting from a meticulous demolition process (Gyurkó et al., 2019), separation/cleaning steps, effortful storage, and transportation. Moreover, as historical AAC blocks do not comply with today's requirements for i. e. thermal protection, areas of application would be limited. Therefore, after the demolition process, a crushing and grading of pd-AAC have to be carried out (Kreft, 2016) to separate pd-AAC granulate (grain size >1 mm) from pd-AAC powder (grain size 0–1 mm). After further sorting, the purified pd-AAC granulate and powder can be used for different recycling options. Fig. 1 shows the pd-AAC landfilling and recycling processes.

First, closed-loop recycling options were investigated. Theoretically, closed-loop recycling could establish a closed material loop. In practice, pd-AAC can substitute primary raw materials in AAC production up to a given threshold, which depends on the density class of the intended AAC product. Kreft (2017) investigates the use of pd-AAC powder in the production of new AAC, substituting the primary resources sand, cement, lime, and anhydrite (Kreft, 2017). Rafiza et al., (2019); Rafiza et al. (2022) and Lam (2021) describe it as well. However, they investigate the substitution of sand with up to 50% (Rafiza et al., 2019; Rafiza et al., 2022) respectively 100% (Lam, 2021) AAC powder, but it is unclear if the used AAC powder stems from post-demolition or production wastes with higher purity. Another way to achieve closed-loop recycling for pd-AAC is to produce intermediate products for AAC production. Stemmermann (2019) and Ullrich et al. (2021) investigate the production of belite cement clinker made from pd-AAC powder that can again be used for producing AAC or other mineral materials. Furthermore, this approach could lead to a reduction in energy consumption, the separation of valuable and associated harmful substances, and the production of a high-quality product. However, data on energy consumption of the belite cement clinker production and recipes for AAC or other material production from belite cement clinker are still missing. Therefore, this new recycling approach cannot be included in this study.

Besides, there are various open-loop recycling options for pd-AAC. First, pd-AAC powder can substitute primary raw materials in cement clinker production. Schoon et al. (2013) conducted a feasibility study including various pd-AAC samples and varying samples with primary clinkers from different sources. They conclude that pd-AAC recycling in cement clinker production is possible but unpractical due to a high energy demand for water evaporation and potential contaminants in the pd-AAC (Schoon et al., 2013). Other research also confirms that only production waste with significantly lower impurities than pd-AAC can be used (Vogel et al., 2011). Also, pd-AAC powder can be used as a filler or supplementary material in the concrete leading to increased strength and durability (Gyurkó et al., 2019). Moreover, pd-AAC powder is used to produce light mortar (Aycil et al., 2016) in laboratory tests. A mixture of pd-AAC powder and granulate can also be recycled in floor screed to replace sand (Bergmans et al., 2016). However, sulphate leaching from pd-AAC is problematic for this application and the recycling of pd-AAC in general (Bergmans et al., 2016). Nevertheless, in floor screed, the sulphate can react with the cement binder forming insoluble ettringite (Bergmans et al., 2016). Similarly, Zou et al. (2022) show that pd-AAC can substitute sand in mortar. Besides, a mixture of pd-AAC powder and granulate can be used to produce lightweight aggregate concrete (LWAC) (Aycil et al., 2016) in laboratory tests. Gyurkó et al., (2019) also investigate an LWAC composition based on a mixture of both pd-AAC powder and pd-AAC granulate and a composition based on pd-AAC granulate only. However, the production of a load-bearing LWAC requires high cement amounts, and the LWAC has relatively low strength and frost resistance, reducing its application potential (Gyurkó et al., 2019). Finally, pd-AAC granulate can be used to produce no-fines concrete, a concrete type without any fine aggregates like sand, with applications as a self-supporting wall, stumped concrete with decorative function (exposed concrete), and shuttering blocks (Gyurkó et al., 2019). In the following, the focus lies on the application as shuttering block.

Additionally, several other open-loop recycling options for pd-AAC granulate outside the construction sector are discussed in the literature: bioactivation for methane emission reduction in landfills (Bukowski et al., 2015), filter material for phosphorus wastewater (Renman and Renman, 2012), soil conditioner (Niedersen et al., 2004), soil materials and fertilisers (Volk and Schirmer, 2010), construction of ponds, canal bases and embankments (Rühle and Maiwald, 2018). However, there are no comparable primary products; thus, an assessment beyond the pd-AAC granulate is impossible. Therefore, these recycling options were excluded from the following life cycle assessment.

Much research focuses on the LCA of building materials (e.g. Christoforou et al., 2016; Jonsson et al., 1998; Mitterpach and Štefko, 2016; Zimele et al., 2019). Additionally, innovative ideas and the use of secondary material in building materials' production are assessed in many studies using LCA (e.g. Ahmed and Tsavdaridis, 2018; Colangelo et al., 2018; Bories et al., 2016; Knoeri et al., 2013). Also, there is research on AAC produced with recycled content (Nühlen et al., 2020). However, pd-AAC recycling options have not been assessed to a large extent, nor are respective LCA data available in the literature. Thus, the central research gap addressed by this study is the environmental assessment of closed-loop and open-loop[2] recycling of pd-AAC in construction materials. Furthermore, the comparison of different pd-AAC recycling options is missing in the literature and will be carried out in this study. Thus, the research objective is to answer whether pd-AAC recycling in

[1] Expert interview with Xella Technologie- und Forschungsgesellschaft mbH.

[2] Closed-loop recycling means using the pd-AAC after processing steps in the production of new AAC products. In contrast, open-loop recycling options use pd-AAC to produce other (construction) materials than AAC.

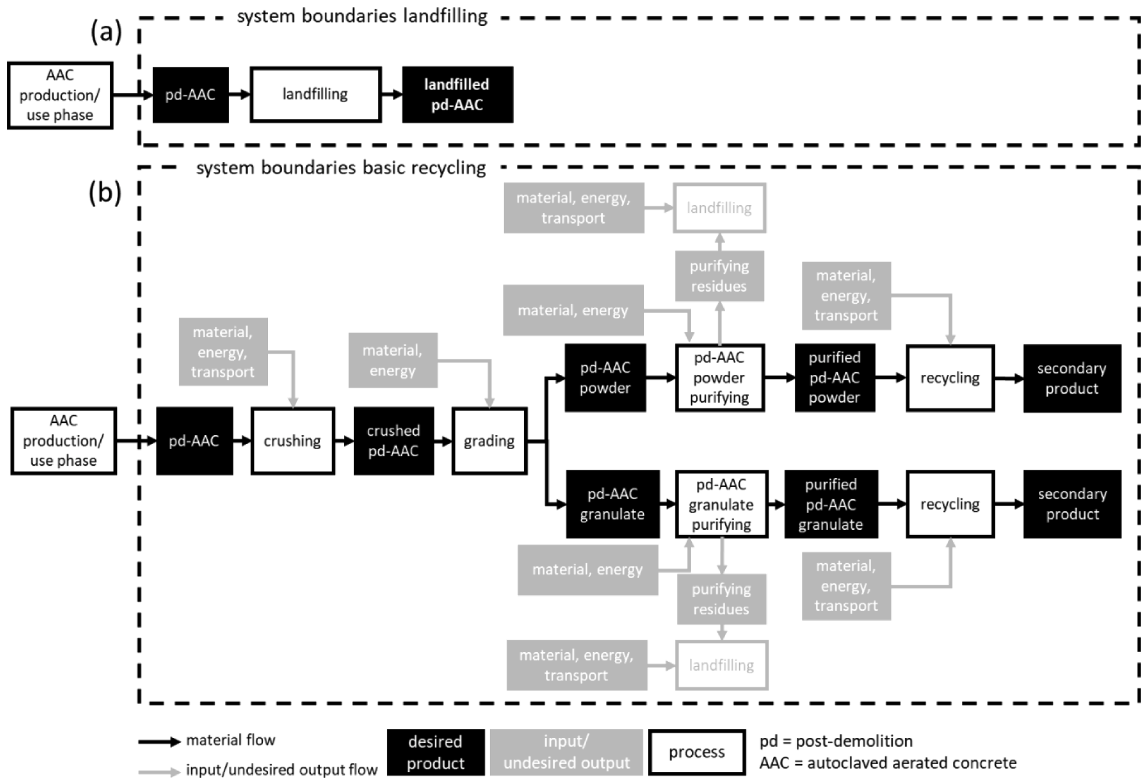

Fig. 1. Overview of (a) the pd-AAC landfilling and (b) the basic pd-AAC recycling process, including crushing, grading, and purifying steps.

construction materials can be environmentally beneficial and which recycling options show the lowest environmental impacts. In the following, the assessment methodology is described (Section 2). This section is followed by the impact assessment, a sensitivity analysis, and a discussion of shortcomings (Sections 3 and 4). Finally, the results are concluded (Section 6).

2. Methods

2.1. Materials

In this paper, different end-of-life options for pd-AAC were compared using LCA. On the one hand, landfilling as the state-of-the-art end-of-life option for pd-AAC is included in the comparison. On the other hand, several recycling options are investigated. First, closed-loop recycling of pd-AAC in AAC production is considered. There are studies investigating this recycling option where pd-AAC powder substitutes sand respectively all primary AAC inputs. In contrast to closed-loop recycling, different open-loop recycling options focusing on construction materials are included in the comparison. Pd-AAC powder can be used as supplementary material in concrete production or as a substitute for primary sand and lightweight aggregates in light mortar production. A mixture of pd-AAC powder and granulate can be recycled in the floor screed production by substituting sand or in the LWAC production by substituting lightweight aggregates. Moreover, pd-AAC granulate can be used to produce shuttering blocks made from no-fines concrete, also substituting lightweight aggregates. Production recipes for these considered recycling options and assumptions are explained in detail in the section on the inventory analysis (Section 2.3).

2.2. Methodological framework (goal and scope)

The goal was to determine whether recycling of pd-AAC is superior to landfilling and which recycling options perform the best. Furthermore, total savings from implementing a beneficial recycling strategy were calculated.

LCA follows the cradle-to-grave approach, which includes all processes from providing the resources to production, use phase, and end-of-life. The final output of the production usually serves as the functional unit. However, for LCA focusing on the end-of-life stage, the so-called zero-burden approach can be applied to meet the particular characteristics of end-of-life assessment by adjusting two significant aspects (Nakatani, 2014): the system boundaries and the functional unit. Concerning the system boundaries, the zero-burden approach does not consider the processes until the emergence of waste products (providing resources, production, use phase) to focus on disposal or recycling assessment. This simplification is possible since the processes before end-of-life are identical for every option. The second adjusted aspect is a change of the functional unit. When applying the zero-burden approach to a waste management system, the input (the waste) serves as the functional unit (Nakatani, 2014). A comparison of different end-of-life options without an input-based functional unit would not be meaningful as different amounts of waste are handled in the scenarios. Here, the pd-AAC end-of-life LCAs followed the zero-burden approach to model and analyse the pd-AAC end-of-life processes. Therefore, providing resources, production, and the use phase was not considered, and the functional unit of 1 kg pd-AAC entered the assessed system without any burdens. The system boundaries included the waste product (pd-AAC at the demolition site) and the waste treatment/recycling processes, including their outputs, as shown in Fig. 1.

In closed-loop and open-loop recycling processes, the desired outputs are valuable products with their LCA data but also come with waste-like sorting residues. Therefore, the ISO standard 14,040/14,044 encourages a system expansion to include these outputs in the recycling LCA. Nakatani (2014) introduces two different approaches for system expansion. The avoided burden approach assumes that the recycling process' desired output replaces a primary product. Then, the recycling process gains an environmental credit/reward (subtraction) in its LCA because burdens for the primary production of the replaced product are avoided. In the product basket approach, the desired recycling output is rewarded by crediting (addition) the recycling system with the primary product (inverse to the avoided burden approach). These two approaches lead to different absolute LCA values due to the differing credit sign for the replaced primary product. However, the comparative burdens and the overall statement remain the same (Nakatani, 2014). Therefore, this study uses both methodological options without changing the results. In the following, we chose the system expansion using the avoided burden approach. It allows a more comprehensible graphical presentation of the results as subtracted credits/rewards directly oppose the efforts for the recycling process. And the handling of waste (non--valuable undesired outputs) is also considered (Section 2.3 purifying process).

2.3. Process assessment and inventory analysis

This section describes data sources and assumptions for every process under study. Tables that contain the energy and material inputs and outputs per process, their amounts, uncertainty used for Monte Carlo simulation (Section 3.3), and the references are given in the Supporting Information (SI)-2. Primarily, weight-based amounts of input and output materials were used to achieve the best comparability between the different recycling options and to match the functional unit (1 kg pd-AAC). Conversions from volume- to weight-based amounts are explained in the following where necessary.

The open-source software openLCA was used to model and assess the different end-of-life options. Relevant data, especially recipes for recycling products, are taken from the literature (see below). The ecoinvent 3.6 database was used to assess general processes (crushing, grading, landfilling) and primary production (for substitution credits) and to fill data gaps in the literature. Data from industrial plants is not available for the pd-AAC recycling processes because pd-AAC is mostly backfilled or landfilled today (Section 1). The ecoinvent data quality system was used for a Monte Carlo simulation to conduct a sensitivity analysis. Fig. 2 shows all assessed recycling options, including preparation steps, inputs, outputs, and substitution products.

The **landfilling** of pd-AAC (reference end-of-life option) and purifying residues was assessed using the ecoinvent 3.6 dataset "treatment of inert waste, inert material landfill", which discloses electricity/diesel/heat efforts, occupation, and transformation efforts.

The **crushing** of pd-AAC was assessed based on the ecoinvent 3.6 dataset "rock crushing" using one functional unit as input and 1 kg of crushed pd-AAC as output (without material loss).

The **grading** of crushed pd-AAC is mandatory to separate the pd-AAC powder from pd-AAC granulate since they are generally used for different recycling purposes. Additionally, **pd-AAC powder/granulate purifying** is essential to remove as many adhesions and impurities as possible to enable high-quality recycling. However, there is no data from industrial sites for both processes and no grading or purifying process regarding crushed AAC available in the ecoinvent 3.6 dataset. Therefore, the process "treatment of waste brick, sorting plant" was chosen as an approximation for both processes combined because AAC and bricks are masonries. This process was the best fitting available dataset since it is more suitable than those concerning gravel sorting of (reinforced) concrete. Transport efforts were not considered in this recycling step as it is assumed that pd-AAC is crushed, graded, and purified at the same place. However, the outputs are assumed to be transported 50 km for the final recycling step for all considered recycling options. We assumed the purifying of 1.01 kg input results in 1 kg purified pd-AAC powder/granulate and 0.01 kg residue sorted out. The grading was assumed to have no material loss. The residue was supposed to be landfilled using the above assessment of landfilling. The process efforts were allocated physically to the two outputs, purified pd-AAC powder and purified pd-AAC granulate.

The **AAC production with pd-AAC powder** was assessed according to Kreft (2017) with a substitution of sand, quicklime, cement, and anhydrite and according to Rafiza et al. (2019); Rafiza et al. 2022) and Lam (2021) with a substitution of sand only (Section 1). Therefore, two different LCAs were conducted. The substitution amounts of sand, quicklime, cement, and anhydrite by pd-AAC powder depend on the produced AAC's density class, which influences the relative shares of the primary inputs. Therefore, three different AAC density classes were considered: AAC-0.35 (class “0,35”, density 305–350 kg/m^3), AAC-0.50 (class “0,50”, density 455–500 kg/m^3), and AAC-0.55 (class “0,55”, density 505–550 kg/m^3) (German Institute for, 2018; German Institute for, 2015). Table 1 displays typical production recipes for above mentioned AAC density classes. Indicated input share intervals result from the fact that manufacturers have to adapt their production formulations to local raw material qualities (e.g. lime reactivity, sand purity and fineness) and the process technology available on site (various production technologies exist side by side that have evolved historically and were or are partly protected from each other by patents). The recipes provide shares for the main inputs for AAC production, excluding additives but including primary AAC powder from AAC production breakage. The centre of the input share intervals of Table 1 was chosen for the subsequent assessment. Data on further primary inputs like energy was based on the ecoinvent 3.6 dataset "autoclaved aerated concrete block production". For substitution, it was assumed that all primary raw materials are replaced according to their input share. The larger the share, the more is substituted by pd-AAC powder. A low and a high substitution were considered for every density class. The high substitution is the maximum substitution realisable in practice without production-related disruptions and without violation of normative specifications or other quality requirements on the final product. To ensure this, prototypes with increased powder content were developed first on “laboratory level” at the small-scale pilot plant of the Xella Technologie- und Forschungsgesellschaft mbH (hereinafter referred to as XTF). In 2021, the new formulations were successfully validated by up-scaling to a production-typical casting volume of 5 m^3 at XTF's large-size pilot plant. According to our current knowledge, the increased powder shares do not have negative impacts on product properties (i.e. compressive strength), and the first test productions at Xella AAC plants according to the new formulations are currently implemented.

The low substitution is five percentage points below the high substitution and indicates the assumed minimum degree that can be implemented even in unfavorable framework conditions (again raw material properties and type of production technology).

Thus, assumed weight-based input shares for pd-AAC powder were 2% (low) and 7% (high) for density class AAC-0.35, 2% (low) and 7% (high) for AAC-0.50, and 5% (low) and 10% (high) for AAC-0.55. Overall, AAC powder input (primary and pd-AAC powder) in the high substitution case sums up to 16% (AAC-0.35) and 21% (AAC-0.50 and AAC-0.55).

Rafiza et al. (2019) and Rafiza et al. (2022) investigated AAC production recipes with between 15% and 50% of sand substituted by pd-AAC powder. Results for this lower and upper interval limit (low/-high substitution) are shown in Section 3.1. Results for substitution rates in this interval can be directly calculated due to a linear relationship because only one primary input is substituted. Lam (2021) investigated AAC production recipes with up to 100% sand substituted by AAC powder but found that the maximum substitution for meeting crucial requirements is 25%. Therefore, the 50% substitution investigated by Rafiza et al. (2019) and Rafiza et al. (2022) stays the upper interval limit for the LCA in this study. The assessment of primary production, recipes after the sand substitution, and rewards for substituting primary AAC were based on the ecoinvent 3.6 dataset "autoclaved aerated concrete block production", which considers AAC of the density class AAC-0.50.

The **concrete production** assessment using pd-AAC powder was based on the ecoinvent 3.6 dataset "concrete production 25–30 MPa", which was also used to calculate the substitution rewards of primary concrete. This concrete was chosen because Gyurkó et al. (2019) state the strength class of the investigated concrete as C25/30. Input amounts of pd-AAC powder, cement, gravel, and sand followed Gyurkó et al.

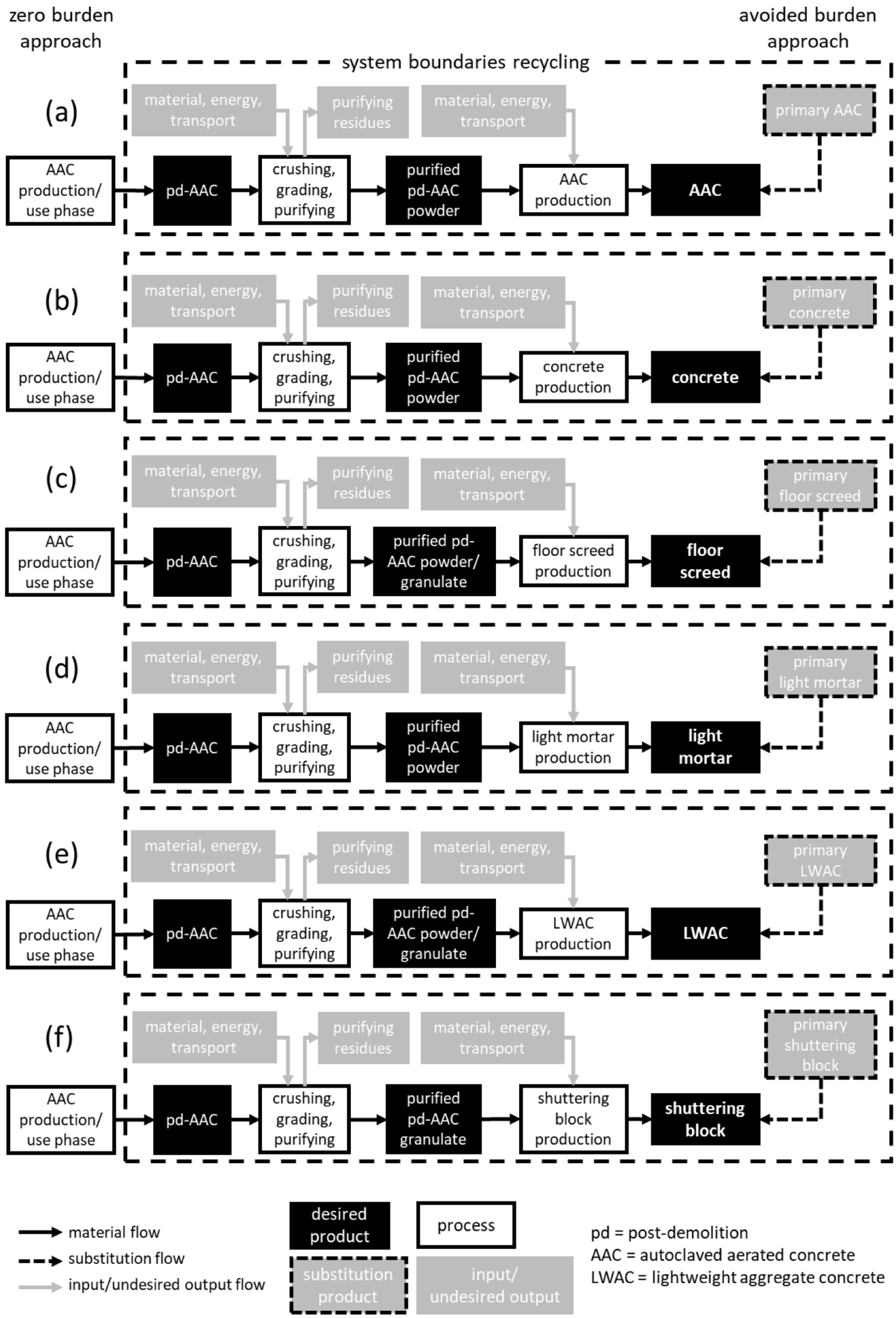

Fig. 2. Assessed pd-AAC recycling options in the construction sector, including (a) AAC production (closed loop), and open-loop options (b) concrete production, (c) floor screed production, (d) light mortar production, (e) LWAC production, and (f) shuttering block production.

(2019): The cement amount was directly given (270 kg/m^3), and the pd-AAC powder was specified as 10% of this (27 kg/m^3). The amount of gravel includes 4/8 mm and 8/16 mm aggregates (1055 kg/m^3), while the sand amount corresponds to the 0/4 mm aggregate amount (936 kg/m^3). Substituted primary concrete production inputs equal these amounts, so the products are directly comparable, and the pd-AAC powder's environmental impact can be revealed.

Aycil et al. (2016) provide a **light mortar production** recipe using pd-AAC powder. For the assessment, the amounts for pd-AAC powder, aluminium, cement, organic chemicals, and water were given by Aycil et al. (2016). Further efforts like electricity or packing were taken from the ecoinvent 3.6 dataset "light mortar production". This dataset also served as the primary light mortar substitution reward.

In the **floor screed production** using pd-AAC powder and pd-AAC

Table 1
Primary AAC production recipes for different density classes.

AAC density class	AAC-0.35	AAC-0.50	AAC-0.55
Input share sand	36%–40%	43%–47%	51%–55%
Input share quicklime	13%–15%	16%–18%	13%–15%
Input share cement	29%–33%	18%–20%	15%–17%
Input share anhydrite	4%–6%	2%–4%	2%–4%
Input share primary AAC powder	7%–9%	12%–14%	9%–11%

granulate investigated by Bergmans et al. (2016), amounts for pd-AAC, cement, and water are directly given. These were used for the assessment after conversion to a mass-based output using the floor screed density (1.75 t/m^3 as the sum of all inputs, Bergmans et al., 2016). However, Bergmans et al. (2016) only provide the total amount of "AAC aggregate" without disclosing pd-AAC powder and granulate shares. As the pd-AAC is crushed before usage in the floor screed (Bergmans et al., 2016), a share of approximately 75% powder and 25% granulate were assumed (Section 1). However, pd-AAC powder and granulate efforts are the same (see above), so its distribution does not influence the LCA results. Other inputs like primary sand and electricity were taken from the ecoinvent 3.6 dataset "cement cast plaster floor production", which was also used for primary floor screed rewards/assessment. The mortar production using pd-AAC, as described by Zou et al. (2022), was not separately included in the comparison as results would be very similar to those of the floor screed production.

The **LWAC production** using pd-AAC powder and pd-AAC granulate was investigated by Aycil et al. (2016) and Gyurkó et al. (2019). Fundamental inputs and emissions were taken from the ecoinvent 3.6 dataset "lightweight concrete block production, expanded clay". The LWAC recipe (option 1) by Aycil et al. (2016) includes amounts for pd-AAC powder, pd-AAC granulate, cement, water, and hard coal ash, which were used for the assessment. Gyurkó et al. (2019) also provide a recipe for their investigated LWAC (option 2) from pd-AAC powder and granulate, including intervals of amounts for AAC aggregate, cement, and water. In the assessment, the centres of these intervals were considered. Based on a grain size distribution (Gyurkó et al., 2019), a 40% powder (< 1 mm) and 60% granulate (> 1 mm) allocation of AAC aggregates was assumed. The required water amount was calculated using the water-cement ratio and the cement amount. Gyurkó et al. (2019) also investigated LWAC production (option 3) only using pd-AAC granulate. Again, amounts for AAC aggregate, cement, and water were given. This data was handled the same way as the other recipe (option 2). The assessment of the reference primary LWAC production was entirely based on the ecoinvent 3.6 dataset "lightweight concrete block production, expanded clay".

Besides, Gyurkó et al. (2019) investigated the recycling of pd-AAC granulate in **shuttering blocks** made of no-fines concrete. Again, a recipe disclosed input amounts of pd-AAC granulate, cement,[3] and water and was used for the assessment. The water amount is calculated using the water-cement ratio. However, there is no ecoinvent 3.6 dataset on "no-fines concrete" or "shuttering block production". Therefore, the dataset "lightweight concrete block production, expanded clay" was used for this purpose. The main difference between LWAC and no-fines concrete is the existence of fine aggregates in LWAC. Still, the production processes are alike, so it is assumed that this process adequately represents no-fines concrete/shuttering block production. The primary shuttering block production inputs are identical to those described in Gyurkó et al. (2019), but the pd-AAC granulate is replaced by primary expanded clay.

3. Results

3.1. Life cycle impact assessment

The following results compare all available pd-AAC recycling options in literature and research based on energy and material balances in a life cycle impact assessment (LCIA). The LCIA reflects the specific case of Central Europe/Germany. So, all input providers were chosen to be from the German/European area if possible.[4] The "ILCD 2.0 2018 midpoint" (ecoinvent, 2019) method was chosen for LCIA. Table 2 shows which midpoints are included in the ILCD 2.0 2018 method. Selected results for each midpoint are presented in the main text. The remainder can be found in SI-1. All numbers used to create the figures are given in the SI-2. First, pd-AAC landfilling and basic processing (crushing, grading, purifying) are compared (Fig. 3).

Transport distances were assumed to be 50 km for both end-of-life options, so these efforts (grey) are identical comparing landfilling and processing for recycling. Further landfilling efforts (red) include the construction of the landfill and energy demand for waste handling and landfill management, especially diesel used in landfill machinery. These landfilling efforts are a bit more impacting than the transport for most midpoints. In contrast, processing for recycling efforts consists of crushing (yellow), grading and purifying (green) and purifying residues treatment (blue). The purifying residues treatment only marginally contributes to the overall impact as only 0.01 kg residues per kg pd-AAC are assumed to be sorted out during the purifying process. Electricity demand is critical for crushing, grading, and purifying efforts. However, grading and purifying contribute significantly more to the overall effort than the crushing, as the total energy demand is around five times higher. Strikingly, overall landfilling impacts exceed the overall processing for recycling impacts for most midpoints. Only concerning freshwater eutrophication, landfilling is environmentally preferable to pd-AAC basic processing. Therefore, the recycling options outperform landfilling if the substitution credits are higher than additional recycling efforts. As a second step, overall results, including substitution credits, were calculated (Fig. 4).

The recycling options of AAC production (sand substitution) and floor screed production have the most negligible substitution credits because only primary sand, which is not associated with high ecological efforts, is substituted. Therefore, these options hardly outperform landfilling in most midpoint categories. But, all other recycling options included in this study show a significant reduction in ecological impacts compared to landfilling. The pd-AAC recycling in concrete production offers higher substitution credits than the recycling options mentioned before. Still, overall savings are lower than in the AAC, light mortar, LWAC, and shuttering block production. The closed-loop recycling of pd-AAC in the AAC production substituting sand, cement, quicklime, and anhydrite shows high substitution credits and the best overall savings concerning CO_2-Eq emissions. There is hardly any difference between the low and high substitution scenario because the functional unit is 1 kg pd-AAC. However, in the high substitution case, more pd-AAC could be used as input to substitute more primary resources. Thus, the environmental efforts per kg AAC are lower than in the low substitution case (Section 4). The substitution credit and the overall savings decrease for higher AAC density classes in all midpoints. Higher AAC density is associated with higher sand and a lower cement content (Table 1), leading to higher sand and lower cement substitution. Thus, substitution credits decrease as cement is associated with significantly higher ecological burdens than sand. However, savings remain significant and higher than in AAC sand substitution and concrete recycling options,

[3] Gyurkó *et al.* (2019) specifies the cement input as 300 litres/m^3 shuttering block respectively 100 kg/m^3. However, this would equal a non-realistic cement density of 0.33 t/m^3. Therefore, it is assumed that these values are unintentionally mixed up and the input amount of cement is 100 litres/m^3 shuttering block respectively 300 kg/m^3 which would equal a realistic density of 3 t/m^3.

[4] The priority for the provider selection was: Germany > Europe without Switzerland / Europe > Rest-of-the-World / Global.

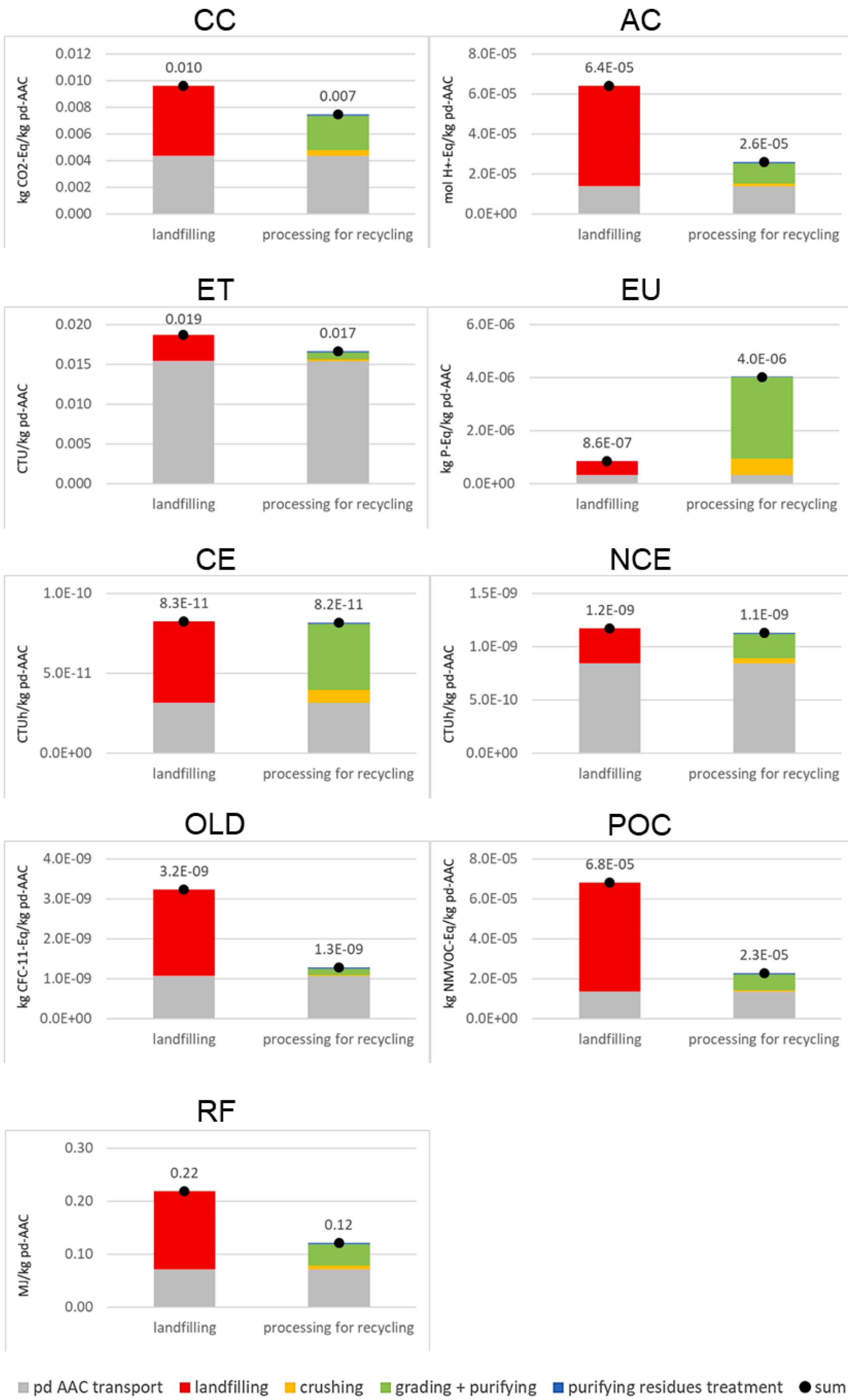

Fig. 3. Impact assessment of landfilling (left vertical-bar in all sub-diagrams) and basic processing for recycling (right vertical-bar in all sub-diagrams) of 1 kg pd-AAC (CC: climate change total, AC: freshwater and terrestrial acidification, ET: freshwater ecotoxicity, EU: freshwater eutrophication, CE: carcinogenic effects, NCE: non-carcinogenic effects, OLD: ozone layer depletion, POC: photochemical ozone creation, RF: resources – fossils).

Table 2
Overview of LCIA midpoints in the "ILCD 2.0 2018 midpoint" method and where results are provided (Ecoinvent, 2019).

Midpoint	Unit	Results provided in
climate change - climate change biogenic	kg CO_2-Eq	SI
climate change - climate change fossil	kg CO_2-Eq	SI
climate change - climate change land use and land use change	kg CO_2-Eq	SI
climate change - climate change total	kg CO_2-Eq	section 3
ecosystem quality - freshwater and terrestrial acidification	mol $H+$-Eq	section 3
ecosystem quality - freshwater ecotoxicity	CTU	section 3
ecosystem quality - freshwater eutrophication	kg P-Eq	section 3
ecosystem quality - marine eutrophication	kg N-Eq	SI
ecosystem quality - terrestrial eutrophication	mol N-Eq	SI
human health - carcinogenic effects	CTUh	section 3
human health - ionizing radiation	kg U235-Eq	SI
human health - non-carcinogenic effects	CTUh	section 3
human health - ozone layer depletion	kg CFC-11-Eq	section 3
human health - photochemical ozone creation	kg NMVOC-Eq	section 3
human health - respiratory effects, inorganics	disease incidence	SI
resources - dissipated water	m^3 water-Eq	SI
resources - fossils	MJ	section 3
resources - land use	Points	SI
resources - minerals and metals	kg Sb-Eq	SI

even for the high-density AAC-0.55 production. In many midpoint categories except climate change, light mortar, LWAC, and shuttering block production show higher substitution credits and savings than AAC production. Mainly, expanded clay is substituted by pd-AAC in all three recycling options. This substitution leads to notable credits as expanded clay is associated with relatively high impacts, for example, 0.44 kg CO_2-Eq/kg. The light mortar production savings are slightly lower than the LWAC and shuttering block production savings for most midpoints. Regarding the different production recipes for LWAC mentioned in the literature, recycling option 2 shows the lowest substitution credit and savings. Option 1 favours the climate change midpoint, as this production recipe has the lowest cement content. Option 3 performs the best for most other midpoints despite a recipe with a higher cement content since expanded clay is substituted by less pd-AAC. Generally, LWAC production (option 3) shows the highest savings of ecological efforts for most midpoints among all recycling options. The shuttering block production outperforms the LWAC production concerning the midpoint climate change but is slightly behind LWAC production for most other midpoints.

3.2. Interpretation

Recycling pd-AAC in the AAC production of different density classes is an excellent option, particularly if cement, quicklime, and anhydrite are substituted. Especially CO_2-Eq emissions could be significantly reduced to 0.49 kg CO_2-Eq/kg pd-AAC compared to landfilling. Further beneficial recycling options include the production of light mortar, LWAC, and shuttering blocks – the latter made from no-fines concrete. These options could also reduce CO_2-Eq emissions and reach savings per kg pd-AAC compared to landfilling of up to 0.43 kg CO_2-Eq, 7 MJ fossil resources, 0.005 mol $H+$-Eq (acidification), 0.17 CTU (freshwater ecotoxicity), 0.2 g P-Eq (freshwater eutrophication), 5.2×10^{-9} CTUh (carcinogenic effects), 4.4×10^{-8} CTUh (non-carcinogenic effects), 2.5×10^{-5} g CFC-11-Eq (ozone layer depletion), and 1.6 g NMVOC-Eq (photochemical ozone creation). Overall, there are several recycling options for pd-AAC, which can reduce ecological impacts significantly compared to landfilling.

Finally, total potential savings can be estimated using the example of GHG emissions in Germany (Fig. 5). For this estimation, the available pd-AAC was assumed to be used in the described recycling options in the literature in descending order of their GHG efficiency. First, as much as possible pd-AAC was considered to be used for AAC production because its GWP substitution credits are the highest. In Germany, around 0.7 million t of pd-AAC was expected to be generated in 2022 (Steins et al., 2021). This could be recycled in the production of AAC-0.35, AAC-0.50, and AAC-0.55, where it substitutes sand, cement, quicklime, and anhydrite. High pd-AAC substitution percentages were assumed to be 7%, 7%, and 10% for the respective AAC products (Section 2.3) at shares of 45% for AAC-0.35, 20% for AAC-0.50 and 10%[5] for AAC-0.55 of the overall AAC production of 3.5 million m^3. Under these assumptions, around 80,600 t of pd-AAC (11.5% of the total pd-AAC amount) could be used for the production of AAC in Germany today. However, due to the limited substitution in AAC production, recycling options of light mortar production, LWAC production, and shuttering block production should also be considered for the remaining pd-AAC material.

In Germany in 2022,[6] 2.7 million t of masonry mortar and interior plaster are expected to be produced, which are the main application options for light mortar (Aycil et al., 2016). And 900,000 t LWAC is expected to be produced (GENESIS, 2021). Shuttering block production is not disclosed in the official production statistics, so it is assumed that they account for 50% of the category "other concrete building blocks and bricks" with a total annual production of 390,000 m^3 (GENESIS, 2021). Thus, we assumed a shuttering block production of 135,000 t with a density of 0.7 t/m^3 (Gyurkó et al., 2019). According to literature, the possible input shares of pd-AAC are much higher for these recycling options than for recycling in AAC, summing up to 61% (light mortar), 81% (LWAC option 1), and 36% (shuttering block) (Aycil et al., 2016; Gyurkó et al., 2019). However, substitution rates might vary between producers because of varying recipes and different product qualities and requirements. After supplying the closed-loop AAC recycling options, the remaining pd-AAC was assumed to be first used for shuttering block production (up to 48,000 t of pd-AAC) due to higher GWP substitution credits than light mortar and LWAC production. The remaining pd-AAC could be equally used for light mortar and LWAC recycling options.

Potential GHG emissions savings were calculated using the difference between landfilling and respective recycling options per assigned pd-AAC mass flow (Fig. 4a). Under the given assumptions, more than 280,000 t CO_2-Eq could be saved via pd-AAC recycling in Germany in 2022 (Fig. 5b). Besides, a landfill capacity of 1.386 million m^3 respectively 693,000 t could have been saved in Germany in 2020 if 1% of purifying residues still were landfilled.

3.3. Sensitivity analysis through Monte Carlo simulation

A Monte Carlo Simulation was performed to investigate the sensitivity of the LCA results. This simulation was based on the ecoinvent data quality system that assesses the reliability, completeness, temporal correlation, geographical correlation, and further technological correlation of the data to determine an uncertainty function. Uncertainty values were taken from the ecoinvent 3.6 database as far as possible. The uncertainty of the remaining inputs that were only described in the literature (Section 2) was determined based on information on data origin (measurements or estimates), the extent of the production sites under consideration, actuality of the study, area of the study, and technological comparability (laboratory data or field data). Finally, a lognormal distribution with standard deviation calculated from the uncertainty values was used for the simulation. All primary production, basic recycling, and final recycling processes were included in the Monte Carlo Simulation, with 10,000 runs for each process. All results of the

[5] The remaining 25% market share is distributed among different AAC products including reinforced AAC wall- and roof-elements.

[6] Production statistics for 2022 are not available yet. Therefore, the production statistics for 2020 and 2021 are used for prediction. The produced amounts did not significantly change over the last two years for all relevant materials. Thus, we assume a constant production amount for 2022.

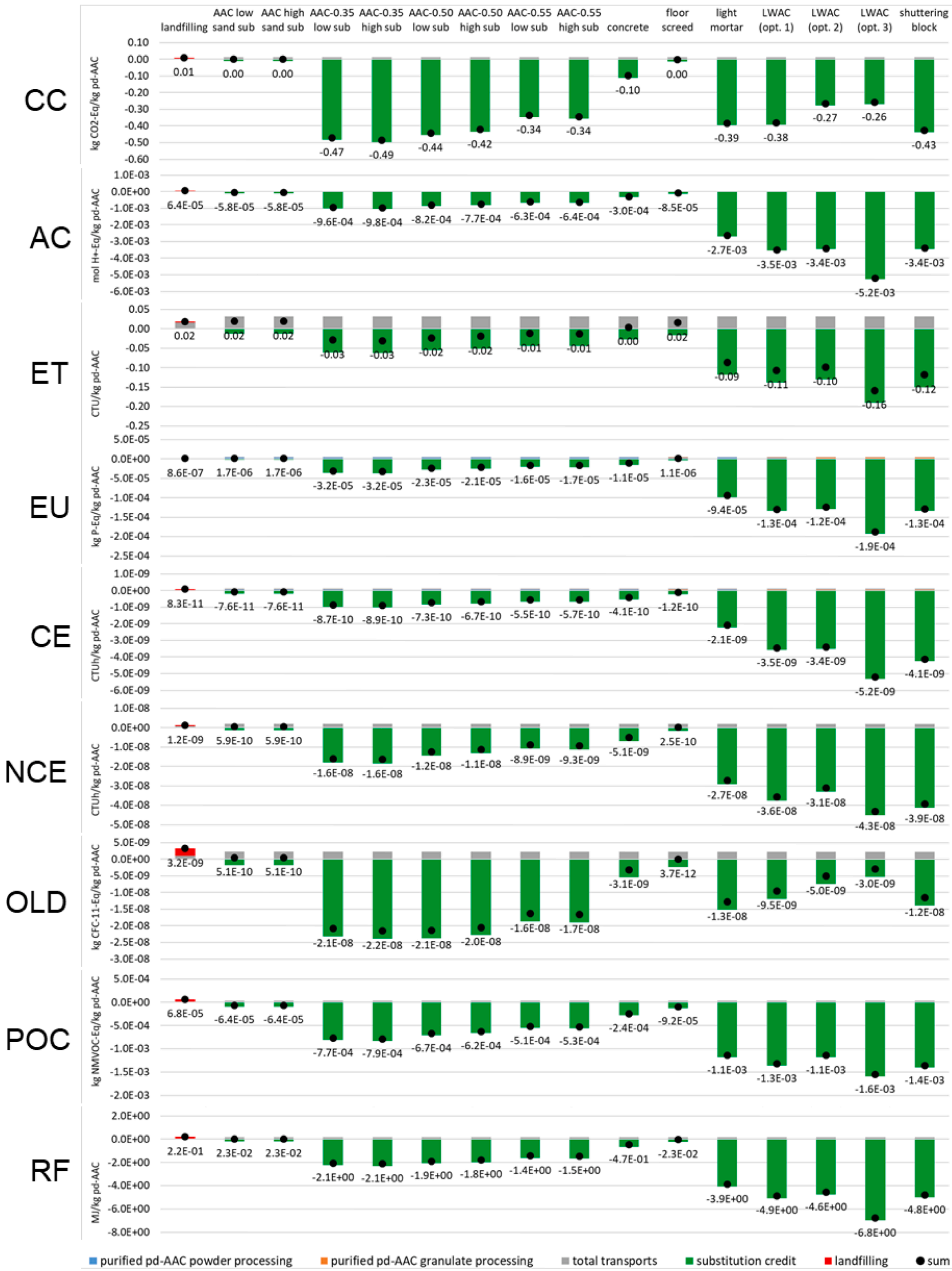

Fig. 4. Impact assessment of landfilling and various recycling options for 1 kg pd-AAC (CC: climate change total, AC: freshwater and terrestrial acidification, ET: freshwater ecotoxicity, EU: freshwater eutrophication, CE: carcinogenic effects, NCE: non-carcinogenic effects, OLD: ozone layer depletion, POC: photochemical ozone creation, RF: resources – fossils).

Monte Carlo Simulation, including mean, median, standard deviation, minimum, maximum, and 25%/75% percentile, are given in the SI-2.

The Monte Carlo simulation results show a median value of all runs near the initially calculated value (Fig. 4) for all processes and all midpoints as expected. Absolute deviations between the originally calculated value and median of the Monte Carlo simulation for the climate change total midpoint are the highest for the AAC production (low sand substitution) and shuttering block production with 0.011 kg

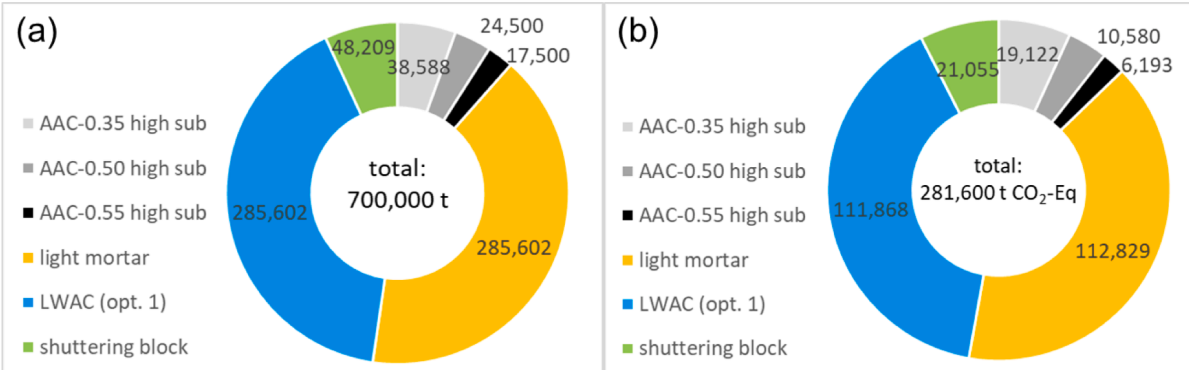

Fig. 5. Recycling strategy for pd-AAC in Germany minimising GHG emission, (a) allocation of the total pd-AAC waste in 2022 [t], (b) allocation of the savings in GHG emissions per chosen recycling option [t CO_2-Eq].

CO_2-Eq/kg pd-AAC. The other recycling options usually have deviations around 0.005 kg CO_2-Eq/kg pd-AAC or even less, around 1% of the total savings of pd-AAC recycling in AAC-0.35 production. The most exciting deviation over all midpoints and recycling options may be found at the freshwater ecotoxicity of AAC-0.35 (low substitution), where the simulation median of -0.04 CTU/kg pd-AAC differs around a third from the original result of -0.03 CTU/kg pd-AAC. However, interpretation does not change as other recycling options, including light mortar, shuttering block, and LWAC production, still outperform the AAC production in this midpoint with total savings of up to -0.16 CTU/kg pd-AAC. These findings are also valid for the impacts of landfilling and primary production processes used for substitution credit calculation. The Monte Carlo simulation shows that the overall impacts calculated for all recycling options are reasonable.

The variability of the LCA results is investigated through the 25% and the 75% percentile of the simulation results. However, the variability of the final impacts of the different recycling options is hard to calculate as it is influenced by the variability of the production process and the substitution credit. Therefore, both aspects are considered separately. Fig. 6 and the following interpretation investigate variabilities for the climate change total midpoint and only focus on impacts of the production processes without substitution credits.

Different variabilities can be observed for the recycling processes considering the 25% and 75% percentile of the Monte Carlo simulation. AAC and concrete production only show very low deviations of up to +/-10% in the AAC production (sand substitution) case. Considerably higher variations of up to −20% and +25% can be observed in the floor screed, light mortar, LWAC, and shuttering block production. The landfilling shows moderate deviations of +23% and -11%. Overall, the interpretation of the results does not change. The AAC-0.35, the preferred recycling option concerning climate change, only shows little variabilities. Other recycling options, including light mortar, LWAC, and shuttering block production, could reach the same level as AAC-0.35 since the impacts could be as much as 20% lower. Either way, the recycling options perform much better than landfilling.

Variabilities of the substitution credit are generally very similar to those of the production process shown above since the processes are the same except for the pd-AAC content. However, variabilities of the substitution credits for light mortar, LWAC, and shuttering block are up to 20 percentage points lower than that of the production processes. Pd-AAC is used in much higher quantities in these three processes, so they differ more significantly from their primary production process. Further information and all data on variabilities for the other midpoints and the substitution credit can be found in the SI-2.

4. Discussion

Different end-of-life options of pd-AAC were assessed and compared. In most options, pd-AAC was used in the production of new products, and substitution credits for avoided primary production were granted, assuming that the same quality for all products was achieved. However, the quality of recycling products is often lower due to impurities in recycling materials. Such quality reductions of recycling products could also occur in pd-AAC recycling since wallpaper, plaster, dowels, screws, and ceramics are likely to adhere to the pd-AAC and might reduce substitution rates and credits. However, a wide range of normative and manufacturer-specific requirements on building materials exist. We determined that the AAC produced with pd-AAC fulfils the same building material standards as primary products by laboratory test production (Section 2.3). Concerning all other recycling options from the literature, we only considered those where secondary products of high quality can be produced. Thus, if the recycling products fulfil the same building material standards as primary products concerning relevant physical and chemical parameters, the same quality assumption and granting full substitution credit is justified.

Literature shows that all investigated recycling options are suitable for replacing primary products. However, some recycling options could be preferred due to technological aspects not being included in this

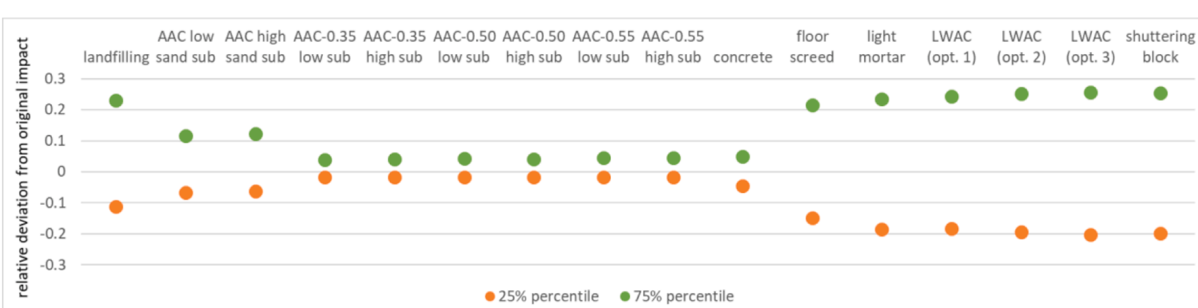

Fig. 6. Variability of the LCA results in a Monte Carlo simulation (25% and 75% percentile) for all recycling options for the midpoint climate change total.

assessment. For example, pd-AAC as aggregate in concrete production performs better than landfilling but worse than some other recycling options concerning the LCA of this study. However, from a technological point of view, pd-AAC improves the strength and durability of the concrete (Gyurkó et al., 2019), which could be a pivotal argument for preferring this recycling option over the others.

Furthermore, two different substitution levels were considered in the closed-loop recycling for three different AAC density classes. The different substitution levels did not show significant differences for any midpoint indicator since the functional unit is 1 kg pd-AAC. However, pd-AAC volumes could soon reach or exceed primary AAC production (Steins et al., 2021). Substitution is currently bound to a few per cent of the AAC production volume, so only a limited share of pd-AAC could be used in closed-loop recycling. Additional savings in environmental efforts between low and high substitution cases reveal when using 1 kg final product as functional unit. Then, primary production of AAC-0.35 is associated with GHG emissions of 0.526 kg CO_2-Eq per kg of AAC, which decreases to 0.516 (-1.9%) in the low (2%) and 0.491 (-6.7%) in the high (7%) substitution scenario. This relationship between primary production, low substitution, and high substitution cases remains the same for the other AAC density classes. Therefore, substitution rates in closed-loop recycling should be maximised to minimise the environmental efforts of the final products. However, pd-AAC shares in AAC production are still quite low and further research and development is required to enhance the shares.

Primary AAC powder emerging from the processing of AAC production leftovers, cutting residues and leftovers returned from job sites is already input for AAC production (Table 1). This primary powder could be replaced by pd-AAC powder to reach pd-AAC powder input shares of up to 21% (Section 2.3). Primary AAC powder is generally cleaner than pd-AAC material and could be used in other recycling options demanding exceptionally high quality. Currently used high-quality applications include, e.g. odour-/ammonia-binders in livestock breeding, fertilisers or soil conditioners. In addition, also calcium silicate units (another masonry product) are produced using AAC powder, albeit mostly in small quantities.

So far, no studies have compared the different end-of-life options of AAC yet. Therefore, the results of this study cannot be directly contextualised with the literature. The input data used for the LCA is taken from different studies. These studies focus on technological aspects and the feasibility of recycling. Currently, the investigations are on a laboratory scale, respectively, on a large-size pilot plant scale in the case of closed-loop recycling (Section 2.3). All proposed production recipes still have to be validated in large-scale production plants. Thus, the input data used for the comparison could still change when the recycling options are implemented more in practice.

5. Limitations

The results and interpretation of this study are based solely on the assessment of ecological factors given the technological descriptions in literature and our own experiments. Economic or social aspects were not considered in this study but could significantly influence the decision of selected recycling options in practice (Section 6).

Additionally, there is no field data for the investigated recycling processes since the performed experiments and data are primarily performed and available on a laboratory scale. Therefore, literature data and the ecoinvent 3.6 dataset were chosen that fit the described processes the best. This approach will likely reflect actual pd-AAC crushing and many primary production processes. However, there is no directly fitting ecoinvent 3.6 or literature dataset for pd-AAC grading and powder/granulate purifying. A dataset for waste brick sorting ("treatment of waste brick, sorting plant – Europe without Switzerland") was chosen for both processes instead, including efforts for a comprehensive treatment process. Hence, pd-AAC grading and purifying effort could have been overestimated.

Moreover, it was assumed that 1% of residue (impurities) is sorted out based on an expert interview. This percentage heavily depends on actual pd-AAC purity and could reach higher values that would decrease process yield and increase ecological burdens of the respective end-of-life option. Additionally, the purifying efforts depend on the desired quality of pd-AAC powder or granulate and their further usage. Application in AAC production is likely to require a high pd-AAC powder quality, whereas applications such as light mortar or floor screed might be practicable with lower grades. Thus, the chosen recycling process determines the effort of the preceding purifying process. This connection was not explicitly considered in the performed LCAs as profound information on the required quality is not available yet. However, the contribution of purifying to the overall result is low.

The potential national savings by pd-AAC recycling are based on literature values and a rough estimation. Thus, this potential might be further limited by technical or logistical restrictions (e.g. small amounts), material, recyclate and product qualities and specific requirements of LWAC, light mortar and shuttering blocks and market sizes/share of products of different grades. Further research is required to reduce uncertainties in this estimation.

6. Conclusion

Life cycle assessment with zero-burden approach and avoided burden system extension were performed to assess the environmental impacts of recycling pd-AAC compared to landfilling. Recycling options considered in this study include the production of AAC (with substitution of sand only or of all primary inputs), concrete, floor screed, light mortar, LWAC, and shuttering blocks made from no-fines concrete. Results show that recycling pd-AAC is advantageous over landfilling in all cases for all environmental criteria analysed since processing pd-AAC is not associated with high impacts and rewards for substituted primary material are significant. Especially the closed-loop recycling of pd-AAC in AAC production can considerably reduce environmental impacts, for example, GHG emissions. Light mortar, LWAC, and shuttering block production are the best open-loop recycling options. These options perform best for the midpoints acidification, eutrophication, ecotoxicity, ozone layer depletion, and resource consumption. Additionally, further open-loop options are needed to cope with the increasing amount of pd-AAC that can be expected in the future.

This study shows that pd-AAC recycling should be fostered because potential annual savings by pd-AAC recycling could sum up to 280,000 t CO_2-Eq and 1.386 million m^3, respectively, 693,000 t of saved landfill capacity in Germany. The legal framework for the processing and recycling mineral demolition waste should support recycling strategies by reducing regional differences in the legislation and in landfilling prerequisites and cost. Besides, political commitment to secondary building materials with recycling content would increase the acceptance and substantially help to enhance recycling. Public construction projects could, for example, contain fixed rates for secondary building materials.

Future research should focus on improved LCA data of said processes, e.g. from pilot plants instead of laboratory data. Furthermore, an economic assessment of the investigated end-of-life options is mandatory to analyse economic viability, transport and handling, significant impacts, influencing factors, and advantageous framework conditions. Right now, landfilling of pd-AAC becomes more expensive as landfill capacities, especially in Germany, decrease. The regional prices exceed 100 €/t in many districts and can reach up to 200 €/t, but differ from district to district. The recycling options presented in this study will likely remain below these costs if transport distances between the demolition place, the recycling plant, and the final production plant can be kept short. Around 30 €/t can be expected for a 100 km transport of pd-AAC using transport costs given by Wolfermann (2016) (adjusted to 2022). Therefore, adding up the costs of two 100 km transports (demolition site to recycling plant and recycling plant to production plant) and the pd-AAC processing could stay below 100 €/t (= landfilling costs) as the processing uses standard processes and only has moderate electricity consumption. However, this rough estimation does not consider revenues for substituted primary material yet.

Further research and regulation should aim for higher substitution ratios, especially in AAC production. Higher substitution rates can reduce the overall environmental impacts and handle increasing pd-AAC amounts in the future.

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Data availability statement

The data that supports the findings of this study are available in the supporting information of this article. Additional data that support the findings of this study are available from the corresponding author upon reasonable request

CRediT authorship contribution statement

Rebekka Volk: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing. **Justus J. Steins:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Oliver Kreft:** Data curation, Funding acquisition, Project administration, Writing – original draft, Writing – review & editing. **Frank Schultmann:** Project administration, Resources, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The data is available in the online supplementary information.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2022.106716.

References

Ahmed, I.M., Tsavdaridis, K.D., 2018. Life cycle assessment (LCA) and cost (LCC) studies of lightweight composite flooring systems. J. Build. Eng. 20, 624–633.

Akhtar, A., Sarmah, A.K., 2018. Construction and demolition waste generation and properties of recycled aggregate concrete: a global perspective. J. Clean. Prod. 186, 262–281.

Anders, N. (2018), "Investigations about porosity analyzing of AAC", ce/papers, Vol. 2 No. 4, pp. 141–145.

Aycil, H., Hlawatsch, F. and Kropp, J. (2016), Hochwertige verwertungsmöglichkeiten für Porenbetonrezyklate [High-quality recycling possibilities for autoclaved aerated concrete recyclates], available at: http://www.abw-recycling.de/r16/17_Fachbeitrag_R16_Aycil.pdf (accessed 7 November 2019).

Bergmans, J., Nielsen, P., Snellings, R., Broos, K., 2016. Recycling of autoclaved aerated concrete in floor screeds: sulfate leaching reduction by ettringite formation. Constr. Build. Mater. 111, 9–14.

Bories, C., Vedrenne, E., Paulhe-Massol, A., Vilarem, G., Sablayrolles, C., 2016. Development of porous fired clay bricks with bio-based additives: study of the environmental impacts by life cycle assessment (LCA). Constr. Build. Mater. 125, 1142–1151.

Bukowski, G., Eden, W., Kuever, J., Kurkowski, H., Lau, J. and Remesch, M. (2015), Bioaktivierung von porenbeton-und kalksandstein-recyclinggranulaten mit methan oxidierenden bakterien zur reduktion von methanausgasungen aus hausmülldeponien - ein beitrag zum klima- und ressourcenschutz – METHANOX II [Bioactivation of recycled autoclaved aerated concrete and sand-lime brick granulates with methane oxidising bacteria to reduce methane emissions from domestic waste landfills - a contribution to climate and resource protection - METHANOX II], *Forschung*sbericht Nr. 118 zum IGF-Forschungsvorhaben 16637 N [Research Report No 118 on the IGF research project 16637 N].

Christoforou, E., Kylili, A., Fokaides, P.A., Ioannou, I., 2016. Cradle to site life cycle assessment (LCA) of adobe bricks. J. Clean. Prod. 112, 443–452.

Colangelo, F., Forcina, A., Farina, I., Petrillo, A., 2018. Life cycle assessment (LCA) of different kinds of concrete containing waste for sustainable construction. Buildings Vol. 8 (5), 70.

Deilmann, C., Krauß, N., Gruhler, K. and Reichenbach, J. (2014), Sensitivitätsstudie zum kreislaufwirtschaftspotenzial im hochbau [Sensitivity study on the circular economy potential in building construction], Forschungsprogramm zukunft bau, aktenzeichen 10.08.17.7-12.29. Im auftrag des bundesinstituts für bau-, stadt- und raumforschung (bbsr) im bundesamt für bauwesen und raumordnung (BBR) [Research programme future construction, reference number 10.08.17.7-12.29. Commissioned by the federal institute for research on building, urban affairs and spatial development (BBSR) at the federal office for building and regional planning (BBR)], available at: https://www.bbsr.bund.de/BBSR/DE/FP/ZB/Auftragsforschung/2NachhaltigesBauenBauqualitaet/2013/Kreislaufwirtschaftspotenzial/01_start.html?docId=1153180&notFirst=true (accessed 18 November 2019).

EAACA (2020), "About EAACA", available at: https://www.eaaca.org/index.php/eaaca#autoclaved-aerated-concrete-aac (accessed 4 March 2020).

ecoinvent (2019), "LCIA methods in ecoinvent v3.6", available at: https://ecoinvent.org/wp-content/uploads/2020/08/list_of_methods_and_indicators_ecoinvent_v3.6.xlsx (accessed 23 August 2022).

European Parliament and Council (2008), Directive 2008/98/EG of the European Parliament and of the council of 19 November 2008 on waste and repealing certain directives.

European Parliament and Council (2011), Regulation (EU) No 305/2011 of the European Parliament and of the council of 9 March 2011 laying down harmonised conditions for the marketing of construction products and repealing council directive 89/106/EEC.

Fouad, F.H. and Schoch, T. (2018), "AAC in the USA - a second look", *ce/papers*, Vol. 2 No. 4, E1–E6.

GENESIS (2021), "Produktionswert, -menge, -gewicht und unternehmen der vierteljährlichen produktionserhebung: Deutschland, jahre, güterverzeichnis (9-Steller) [Production value, quantity, weight and enterprises of the quarterly production survey: Germany, years, list of goods (9-digit)]", GENESIS-Online Datenbank, *Code 42131-0003, available at*: https://www-genesis.destatis.de/genesis/online (accessed 13 October 2021).

German Institute for Standardization (Deutsches Institut für Normung e.V.), *Anwendung von Bauprodukten in Bauwerken – Teil 404: Regeln für die Verwendung von Porenbetonsteinen nach DIN EN 771-4:2015-11 [Application of building products in structures - Part 404: Rules for the use of autoclaved aerated concrete blocks according to DIN EN 771-4:2015-11]*, Vol. 91.100.30 No. 20000-404: 2018, Beuth Verlag GmbH, Berlin.

German Institute for Standardization (Deutsches Institut für Normung e.V.), 2015. *Festlegungen für Mauersteine – Teil 4: Porenbetonsteine [Specification for masonry units - Part 4: Autoclaved aerated concrete masonry units]: German version EN 771-4: 2011+A1:2015*, Vol. 91.100.30 No. 771-4:2015-11, Beuth Verlag GmbH, Berlin.

Grinfel'd, G.I., Vishnevsky, A.A. and Smirnova, A.S. (2018), "Production and use of autoclaved aerated concrete in Russia", ce/papers, Vol. 2 No. 4, pp. 67–71.

Gyurkó, Z., Jankus, B., Fenyvesi, O., Nemes, R., 2019. Sustainable applications for utilization the construction waste of aerated concrete. J. Clean. Prod. 230, 430–444.

Jonsson, A., Bjorklund, T., Tillman, A.-M., 1998. LCA of concrete and steel building frames. Int. J. Life Cycle Assess. Vol. 3 (4), 216–224.

Knappe, F., Dehoust, G., Petschow, U. and Jakubowski, G. (2012), Steigerung von akzeptanz und einsatz mineralischer sekundärrohstoffe unter berücksichtigung schutzgutbezogener und anwendungsbezogener anforderungen, des potenziellen, volkswirtschaftlichen nutzens sowie branchenbezogener, ökonomischer anreizinstrument [Increasing the acceptance and use of mineral secondary raw materials, taking into account requirements relating to the protection of the environment and application, the potential economic benefits and sector-specific economic incentives], Funding reference number: 206 31 304/01, *Texte*, Dessau-Roßlau, available at: https://www.umweltbundesamt.de/sites/default/files/medien/461/publikationen/4305.pdf (accessed 27 December 2019).

Kreft, O. (2016), "Closed-loop recycling of autoclaved aerated concrete. Geschlossener Recyclingkreislauf für Porenbeton", Mauerwerk, Vol. 20 No. 3, pp. 183–190.

Kreft, O. (2017), "Autoclaved aerated concrete with sulphate content: an environmentally friendly, durable and recyclable building material. Sulfathaltiger

Porenbeton: Ein umweltfreundlicher, langlebiger und recyclingfähiger Baustoff", Mauerwerk, Vol. 21 No. 5, pp. 287–296.
Knoeri, C., Sanyé-Mengual, E., Althaus, H.-J., 2013. Comparative LCA of recycled and conventional concrete for structural applications. Int J Life Cycle Assess 18 (5), 909–918. https://doi.org/10.1007/s11367-012-0544-2.
Lam, N.N., 2021. Recycling of AAC waste in the manufacture of autoclaved aerated concrete in Vietnam. Geomate J. Vol. 20 (78), 128–134.
Mitterpach, J., Štefko, J., 2016. An environmental impact of a wooden and brick house by the LCA method. Select. Process. Wood Process. 688, 204–209.
Nakatani, J., 2014. Life cycle inventory analysis of recycling: mathematical and graphical frameworks. Sustainability Vol. 6 (9), 6158–6169.
Niedersen, K.-U., Flick, G. and Memmler, H.-J. (2004), "Porenbetonbruch als bodenverbesserer im landbau [Autoclaved aerated concrete breakage as soil conditioner in agriculture]", Müll und Abfall Fachzeitschrift für Behandlung und Beseitigung von Abfällen, Vol. 36 No. 5, pp. 231–234.
Nühlen, J., Dittrich, S., Maga, D. and Thome, V. (2020), "Herstellung und ökologische bewertung von porenbeton auf sekundärrohstoffbasis [Production and ecological evaluation of aerated autoclaved concrete based on secondary raw materials]", Müll und Abfall, No. 02/2020, pp. 54–59.
OECD (2020), The circular economy in cities and regions: synthesis report, OECD urban studies, OECD Publishing, Paris.
Peduzzi, P., 2014. Sand, rarer than one thinks. Environ. Dev. 11, 208–218.
Rafiza, A.R., Chan, H.Y., Thongtha, A., Jettipattaranat, W., Lim, K.L., 2019. An innovative autoclaved aerated concrete (AAC) with recycled AAC powder for low carbon construction. IOP Conf. Ser.: Earth Environ. Sci. Vol. 268 (1), 12050.
Rafiza, A.R., Fazlizan, A., Thongtha, A., Asim, N., Noorashikin, M.S., 2022. The physical and mechanical properties of autoclaved aerated concrete (AAC) with recycled AAC as a partial replacement for sand. Buildings Vol. 12 (1), 60.
Renman, G. and Renman, A. (2012), "Sustainable use of crushed autoclaved aerated concrete (CAAC) as a filter media in wastewater purification", available at: https://www.diva-portal.org/smash/get/diva2:560089/FULLTEXT01.pdf (accessed 13 July 2020).
Riegler-Floors, P., Hillebrandt, A., 2018. Kostenvergleich konventioneller und recyclinggerechter Konstruktionen [Cost comparison of conventional and recyclable constructions]. In: Hillebrandt, A., Riegler-Floors, P., Rosen, A., Seggewies, J.-K. (Eds.), Atlas Recycling [Recycling atlas]: Gebäude als Materialressource [Buildings as Material Resources]. Detail Business Information GmbH, München, pp. 120–134.
Rühle, G. and Maiwald, H. (2018), Einsatz von porenbetonsteinen, porenbetonbruchstücken und porenbetongranulat in der landschaftsgestaltung und zur lösung von umweltproblemen [Use of autoclaved aerated concrete blocks, autoclaved aerated concrete fragments and granulated autoclaved aerated concrete in landscape design and for solving environmental problems] No. DE102017101684, available at: http://www.freepatentsonline.com/DE102017101684.html (accessed 20 May 2020).
Schoon, J., Buysser, K.de, van Driessche, I., Belie, N.de, 2013. Feasibility study on the use of cellular concrete as alternative raw material for Portland clinker production. Constr. Build. Mater. 48, 725–733.
Steins, J.J., Volk, R. and Schultmann, F. (2021), "Modelling and predicting the generation of post-demolition autoclaved aerated concrete (AAC) volumes in Germany until 2050", *Resou., Conserv. Recycl.*, p. 105504.
Stemmermann, P. (2019), "REPOST recycling cluster porenbeton: teilvorhaben 4: dicalciumsilikat aus porenbetonresten aus abbruchmaßnahmen [REPOST recycling cluster autoclaved aerated concrete: sub-project 4: dicalcium silicate from residual autoclaved aerated concrete from demolition measures]", available at: http://www.itc.kit.edu/downloads/Repost_Steckbrief_de_020919.pdf (accessed 6 March 2020).
UN (2020), "Sustainable development goals", available at: https://www.un.org/sustainabledevelopment/sustainable-development-goals/ (accessed 23 March 2020).
Vogel, S., Ott, D. and Dressel, D. (2011), Neue technologien in der zementproduktion zur reduzierung der CO2-emission [New technologies in cement production to reduce CO2 emissions], available at: https://d-nb.info/1038682533/34 (accessed 25 March 2021).
Volk, J. and Schirmer, P. (2010), "Bewertung der verwendung von porenbetonrezyklaten für die herstellung von bodenwertstoffen und düngemittel [Evaluation of the use of autoclaved aerated concrete recyclates for the production of soil materials and fertilisers]", 22.-23.09.2010, Weimar.
Wolfermann, A. (2016), Transport cost: an aggregated model for surface freight transport based on cost components and market segments, konferenz„ verkehrsökonomik und -politik" [Conference "Transport economics and policy"], available at: https://elib.dlr.de/104581/1/wolfermann-transport_cost_-_an_aggregated_model_for_surface_freight_transport.pdf (accessed 25 January 2022).
Ullrich, A., Garbev, K., Bergfeldt, B., 2021. *In Situ* X-ray diffraction at high temperatures: formation of Ca2SiO4 and ternesite in recycled autoclaved Aerated concrete. Minerals 11 (8), 789. https://doi.org/10.3390/min11080789.
Zimele, Z., Sinka, M., Korjakins, A., Bajare, D., Sahmenko, G., 2019. Life cycle assessment of foam concrete production in Latvia. Environ. Clim. Technol. Vol. 23 (3), 70–84.
Zou, D., Que, Z., Cui, W., Wang, X., Guo, Y., Zhang, S., 2022. Feasibility of recycling autoclaved aerated concrete waste for partial sand replacement in mortar. J. Build. Eng. 52, 104481.