



# Economic Assessment of Post-demolition Autoclaved Aerated Concrete (AAC) Recycling and Subsequent Belite Cement Clinker Production

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Received: 3 March 2025 / Accepted: 13 October 2025  
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## Abstract

Autoclaved aerated concrete (AAC) is a building material with high thermal insulation properties used as masonry units in the construction of residential buildings. Although volumes of post-demolition AAC (pd-AAC) are increasing, it is mainly landfilled today while landfill fees rise, legal framework conditions in Europe are tightening, and climate protection needs extensive efforts in the area of recycling. This study presents an economic assessment of pd-AAC recycling, consisting of mechanical processing (crushing, grading, purifying) and subsequent belite cement clinker production from the fine pd-AAC fraction. The processes are modelled in detail to determine needed equipment, material flows, and energy demands for five different plant capacity scenarios. Calculated total costs of pd-AAC recycling, consisting of variable costs, fixed costs, overhead costs, and general expenses, vary significantly between the different scenarios. Today, mechanical processing of pd-AAC has total costs between 30 €/t input (plant capacity: 250,000 t/a) and around 209 €/t input (plant capacity: 10,000 t/a). The mechanical processing is economically viable compared to regionally varying pd-AAC landfilling costs of 65–180 €/t for recycling plants with capacities of at least 25,000 t/a. Additional costs for subsequent belite cement clinker production from pd-AAC sum up to 800 €/t input (plant capacity: 250,000 t/a), respectively 1250 €/t input (plant capacity: 10,000 t/a). Thus, the minimum sales price for the resulting belite cement clinker would need to be around 430 €/t to compete with current landfilling costs.

**Keywords** Post-demolition autoclaved aerated concrete (pd-AAC) · Recycling · Economic assessment · Industrial ecology · Circular economy

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## Introduction

The building sector has a high and increasing resource consumption and causes vast greenhouse gas (GHG) emissions during construction, operation, and end-of-life. Therefore, considerable savings in the building sector have to be implemented to reach the UN sustainable development goals, particularly “sustainable cities”, “responsible consumption and production”, and “climate action” [1]. Recycling construction and demolition waste (C&DW) is a promising approach for reducing GHG emissions and primary resource consumption. The savings potential is enormous as C&DW exceed 3 billion tons worldwide annually [2]. Furthermore, legal requirements for recycling are getting stricter. For example, the European waste and recycling regulation [3] demands recycling rates of at least 70% for C&DW. But, until now, “the potential of the circular economy to support sustainable cities, regions, and countries still needs to be unlocked” [4].

Autoclaved aerated concrete (AAC) is produced from quartz sand, cement, quicklime, anhydrite/gypsum, aluminium powder/paste, and water [5, 6]. The aluminium powder/paste acts as an aerating agent that forms numerous pores in the AAC during production. The porous structure leads to a low density and excellent thermal insulation properties of AAC, which is the main reason for its high popularity. The current European AAC production exceeds 16 million m<sup>3</sup> annually [7], while approximately 11.6 million m<sup>3</sup> of AAC were produced in Russia in 2017 [8]. The global production capacity is expected to be around 450 million m<sup>3</sup> for non-reinforced AAC blocks [9]. Post-demolition AAC (pd-AAC) volumes are currently increasing. In Germany, an annual pd-AAC volume of 1.4 million m<sup>3</sup> in 2022 and a sharp increase to more than 4 million m<sup>3</sup> in 2050 is expected due to a significant increase in popularity in the 1960s and 1970s [10]. Therefore, its recycling has the potential to reduce disposal needs, save natural resources, and lower greenhouse gas emissions, thus addressing environmental and economic challenges.

Unfortunately, the usual recycling of mineral C&DW in road construction, earthworks, and aggregate in concrete production is impossible for pd-AAC due to the porous structure, relatively low compressive strength, and sulphate content. Besides, adherences and impurities impede recycling [11]. Thus, recycling of pd-AAC is not established yet, and the majority of pd-AAC is backfilled or landfilled, even though landfill fees are expected to rise, and landfilling capacities are limited [12]. Additionally, reusing pd-AAC blocks is impractical due to the immense costs of an extremely careful demolition process [13] and the incompatibility of historical AAC blocks with up-to-date thermal protection requirements. Thus, pd-AAC represents a large and currently underutilised secondary resource.

Current research investigates new possibilities for pd-AAC recycling in the construction sector. Proposed options include the production of new AAC [5, 14–16], floor screed [17], light mortar [18], lightweight aggregate concrete [13, 18], and shuttering block made from concrete without fine fraction [13]. Moreover, pd-AAC powder can be used as a raw material in new AAC production to replace primary resources such as sand, cement, lime, and anhydrite [5]. Other studies examine the partial replacement of sand by pd-AAC in the AAC production with substitution rates of up to 50% [15, 16] or even up to 100% [14]. These studies show the closed-loop recycling options for pd-AAC obtained by the recycling process described and assessed in this paper. All recycling options need the pd-AAC to be crushed, purified and graded. However, they primarily use the pd-AAC granulate (grain size > 1 mm) to replace natural aggregates. Any mechanical treatment also generates a rela-

tively large pd-AAC powder fraction (grain size 0–1 mm; up to 75 wt%) that is difficult to recycle. As pd-AAC volumes are expected to rise [10], recycling options for both fractions are needed.

Ordinary Portland Cement Clinker (OPC), the most widely used construction material, is produced from the raw materials that contain CaO, SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub> and Fe<sub>2</sub>O<sub>3</sub>, with CaCO<sub>3</sub> as a source of CaO required for phase formation. OPC clinker contains alite (Ca<sub>3</sub>SiO<sub>5</sub>), belite (Ca<sub>2</sub>SiO<sub>4</sub>), aluminate (Ca<sub>3</sub>Al<sub>2</sub>O<sub>6</sub>), and aluminoferrite (Ca<sub>2</sub>Al<sub>2</sub>Fe<sub>2</sub>O<sub>8</sub>) phases, with alite being the dominant phase [19]. On the other hand, belite cement clinkers are characterised by dominant belite content. Its formation requires lower CaO, which consequently reduces the amount of CaCO<sub>3</sub> needed.

Belite cement clinker can be synthesised at temperatures as low as 1000 °C when a CO<sub>2</sub> atmosphere is established [20]. Because of the moderate temperature, clinker formation can be achieved in an indirectly heated, electric rotary kiln under a CO<sub>2</sub> atmosphere.

Pd-AAC powder can be used as a raw meal component, replacing primary raw materials like limestone, clays, for producing a recycled belite cement clinker (RC-BCC) in a low-temperature process at 1000 °C [21]. RC-BCC can substitute parts of the ordinary Portland cement needed for new AAC blocks [22] or other applications. RC-BCC produced from pd-AAC is not directly benchmarked against standard OPC. However, within the framework of Repost project, for AAC production, 25% of the OPC was successfully replaced with ground RC-BCC. Existing installations were used for production, and tests showed that the product quality remained the same. Further details can be found in [23, 24].

While multiple dimensions are relevant in assessing recycling technologies, economic feasibility is decisive for their real-world implementation. Cost competitiveness determines whether pd-AAC will be landfilled or recycled. Therefore, this study focuses on a detailed economic analysis. The framework presented here can be extended in future research to include life cycle or multi-criteria perspectives.

This study's economic assessment of pd-AAC recycling focuses on the mechanical processing (crushing, purifying, and grading) required for different recycling options and the RC-BCC production. Data for the latter is from lab and pilot plant tests. The current technology readiness level of the RC-BCC production from demolition wastes is 4–5. Therefore, the exact technology and equipment required to set up a future production plant are not well established, resulting in inaccuracies in the cost assessment of RC-BCC production. Much literature performs (techno-) economic assessments for numerous processes and products. Assessments for recycling processes are also available in the literature, for example, concerning the mechanical [25] and chemical [26] recycling of plastics, lightweight packaging [27], e-waste [28], solar photovoltaic panels [29], lithium-ion batteries [30], agricultural waste [31], and municipal solid waste in general [32]. This study addresses the economic assessment of pd-AAC recycling and subsequent RC-BCC production, which is not available in the literature yet.

Therefore, this study aims to assess the economic feasibility of pd-AAC recycling. Specifically, the study analyses (i) the costs of processing pd-AAC into secondary raw material, (ii) the influence of key parameters such as landfill fees, energy costs, and interest rates, and (iii) the implications for decentralised versus centralised recycling approaches. To achieve this, a transparent bottom-up cost model was developed, complemented by a sensitivity analysis to test the robustness of the results. A conventional economic analysis was deliberately chosen as it provides a transparent basis for assessing the viability of pd-AAC

recycling. More complex tools, such as optimisation models or complete techno-economic assessments, require detailed input data that is not yet available for this emerging field. Thus, the present approach is a benchmark model that can be adapted with regional data and further expanded in future research to include environmental and logistical optimisation. Hence, the research question to be answered in this study is: Under which circumstances can pd-AAC recycling and RC-BCC production from pd-AAC be economically beneficial? The following sections describe the methodology (Sect. "Result") and the results (Sect. "Result"). Then, the results are discussed, and limitations are presented (Sect. "Discussion"). Finally, a conclusion is drawn (Sect. "Conclusion").

## Methods

This section describes how the economic assessment is conducted and which input data is used. First, the supply of pd-AAC is investigated, and the revenue that can be made from the final products is determined (Sect. "Pd-AAC supply and revenue for the final product"). Furthermore, the recycling process is described and illustrated in detail, including information on the mass flows. The mechanical processing is examined in Sect. "Mechanical pd-AAC processing", while the RC-BCC production is described in Sect. "RC-BCC production from pd-AAC powder". Additionally, the economic assessment methodology is disclosed (Sect. "Methodology of the economic assessment"), and scenarios are discussed (Sect. "Scenario definition").

### Pd-AAC Supply and Revenue for the Final Product

In contrast to other countries and regions, detailed information on pd-AAC volumes is available for Germany [10]. Thus, the German case is investigated in this study. In 2022, around 1.4 million m<sup>3</sup> of pd-AAC can be expected [10]. This volume equals 0.7 million t of pd-AAC, assuming a density of 0.5 t/m<sup>3</sup> [10, 11, 33, 34]. Most popular modern AAC has a density of around 0.35 t/m<sup>3</sup>, but, historically, thermal insulation requirements were not as high as today, and AAC's density used to be higher [35]. Most pd-AAC is landfilled today, demanding disposal costs, which is, thus, the comparative value for the recycling process costs. Pd-AAC landfill fees in Germany vary between 65 and 180 €/t [36]. Enquiries in online portals<sup>1</sup> and an expert interview<sup>2</sup> validate this variability, while the average disposal costs for landfilling pd-AAC are around 100 €/t.

The final products of the mechanical processing and purifying of pd-AAC are pd-AAC powder and pd-AAC granulate. These two products can substitute different primary resources depending on their final application. The pd-AAC powder usually replaces sand and, in the case of closed-loop recycling, also partly cement, quicklime, and anhydrite, which are needed for AAC production [37]. The pd-AAC granulate can be used in several open-loop recycling options, serving as a lightweight aggregate substituting, for example, primary expanded clay [37]. Overall, pd-AAC powder/granulate as the final product of the mechanical processing is assumed to reach a sales price of 10 €/t. Actual market prices

<sup>1</sup> The portals abfallscout.de and clearago.de were used.

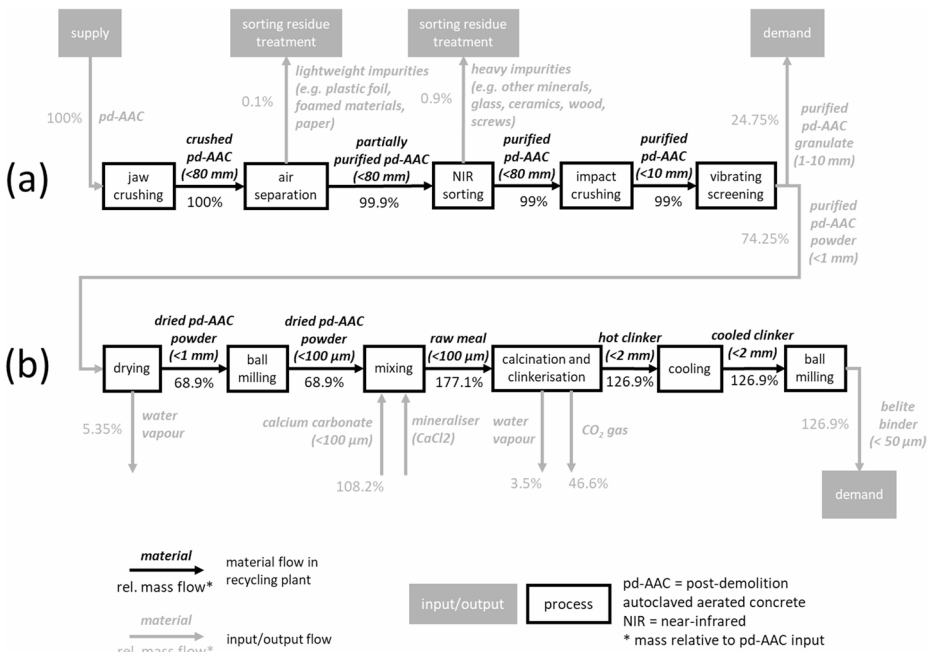
<sup>2</sup> Xella Technologie- und Forschungsgesellschaft mbH, Dr. Oliver Kreft.

for pd-AAC powder or granulate do not exist yet. Research on recycling sand/split/broken rocks showed sales prices between 5 €/t and 15 €/t [38]. Additionally, pd-AAC powder can be used in RC-BCC production. The costs of the RC-BCC production are compared with the average price of ordinary Portland cement prices of 150 €/t [39, 40], as a direct substitution is possible.

### Mechanical pd-AAC Processing

The mechanical processing of pd-AAC consists of crushing, purifying, and grading steps [41, 42]. Krampnitz et al. [42] show that pd-AAC can be treated with established demolition waste processing machinery, especially regarding crushing. Figure 1(a) illustrates the detailed process considered adequate for pd-AAC mechanical processing in this study. First, the pd-AAC is crushed to grain sizes < 80 mm with a jaw crusher. The crushed pd-AAC is then purified using air separation to separate lightweight impurities like plastic foils, foamed materials, and paper. A second purifying step is near-infrared (NIR) sorting. This step can sort out heavy impurities like other minerals, glass, ceramics, wood, and screws. Afterwards, the purified pd-AAC is crushed a second time using an impact crusher to reach the desired grain size of < 10 mm. Finally, a vibrating screen separates the pd-AAC powder (< 1 mm) from the pd-AAC granulate (1–10 mm).

The relative mass flows in the pd-AAC recycling process are also given in Fig. 1(a). In total, 1% of the input mass is assumed to be an impurity that is sorted out [37]. The air separation is supposed to sort out 0.1%, while the NIR sorting is assumed to sort out 0.9% of the total input mass. The final impact crushing is considered to produce pd-AAC powder



**Fig. 1** Schematic representation of (a) the mechanical pd-AAC processing and (b) RC-BCC production from pd-AAC powder, including relative mass flows

and granulate in a proportion of 3:1 [13, 37], leading to an overall output of the mechanical processing of 74.25% pd-AAC powder and 24.75% pd-AAC granulate. Electricity for the machines is the only energy needed for mechanical processing. Electricity demands were researched in machine specification sheets and are given in Sect. "Result" (Table 2). The electricity demand per ton is calculated from the maximal power input and, thus, should be considered as a conservative electricity cost assessment.

### RC-BCC Production from pd-AAC Powder

The resulting purified pd-AAC powder (<1 mm) from the mechanical processing is processed in a multistage process to produce a RC-BCC. This process involves drying, milling, rotary kiln processing, and cooling, as illustrated in Fig. 1(b).

First, the pd-AAC powder is dried to reduce the moisture content. Pd-AAC samples considered in an experimental study by [21] have a moisture content ranging from approximately 9 to 15 wt%. All mass and energy balance calculations in this work are based on 9 wt% moisture, according to [43]. The second step is milling pd-AAC to  $d_{80}=100\ \mu\text{m}$  size. Typically, the pd-AAC has an average molar ratio of  $\text{CaO}/\text{SiO}_2 = 0.5$ , while the formation of belite requires a  $\text{CaO}/\text{SiO}_2$  molar ratio of 2. Therefore, calcium carbonate is added. Furthermore, a mineraliser ( $\text{CaCl}_2$ ) of 2 wt% is added to improve the reaction kinetics. Then, the raw material is fed into an electrical rotary kiln heated to 1000 °C, in which calcination and clinkerisation reactions lead to the formation of belite clinker. The hot clinker is finally fed into a cooler and ground to a size of  $d_{80} = 50\ \mu\text{m}$ .

### Methodology of the Economic Assessment

The calculation of the total costs for pd-AAC recycling and RC-BCC production is based on the methodology of [44]. Total costs are made up of variable costs, fixed costs, overhead costs and general expenses. Variable costs comprise several components, including operating labour, electricity, and maintenance.

The fixed costs are determined by the fixed-capital investment for building a recycling plant, the required working capital, and land costs. The land costs are calculated from the assumed required area for the plant (1 ha in the baseline scenario, scaled with an exponent of 0.9 for the other scenarios) multiplied by the average costs per  $\text{m}^2$  (Table 1). The fixed-capital investment and the working capital are calculated using the "percentage of delivered-equipment cost" approach by [44]. The costs for the required equipment are the basis of this method. Further cost aspects, total fixed-capital investment, and working capital are estimated by multiplying percentages with equipment costs. Included cost aspects and their respective cost percentages of the equipment costs are given in Sect. "Result". The required equipment is derived from Fig. 1. Besides the machines directly shown, a compressed air generation for the NIR sorting and nine conveyor belts (one for each transport, i.e. arrow in Fig. 1(a)) for general product transport through the facility are needed for mechanical processing. The RC-BCC production uses an additional eight conveyor belts. Equipment costs were researched by direct inquiry to manufacturers for jaw crushing, impact crushing, air separation, NIR sorting, vibrating screening, conveyor belts, and compressed air generation. The dryer, the ball mill, and the rotary kiln costs were calculated using the correlation function introduced by [45] and given in Eq. (1).

**Table 1** Relevant primary data and assumptions for the economic assessment of pd-AAC recycling

parameter	value	reference
operational time mechanical processing [h/a]	3,300	assumption (12 h/d, 275 d/a)
operational time RC-BCC production [h/a]	6,600	assumption (24 h/d, 275 d/a)
interest rate [-]	0.07	assumption
share of borrowed capital [-]	1	assumption
service life of the plant [a]	15	assumption
annuity factor [-]	0.11	derived from interest rate and service life of the plant using Eq. (2)
labour costs [€/working hour]	41.90	labour costs in the manufacturing sector in Germany in 2021 [50]
sorting residue treating [€/t]	100	assumption
limestone [€/t]	40	expert interview <sup>a</sup>
CaCl <sub>2</sub> costs [€/t]	92	assumption based on online portals (chemishop24.de, german.alibaba.com)
CO <sub>2</sub> certificate costs [€/t]	85	[51]
electricity costs [€/kWh]	0.265	[52], as of: July 2023
land costs (economically used building land) [€/m <sup>2</sup> ]	63.48	[53], average 2021 value
CO <sub>2</sub> certificate costs [€/t]	85	[51]

<sup>a</sup>Dr.-Ing. Jesko Gerlach, Holcim GmbH.

$$C_e = a + b * S^n \quad (1)$$

- $C_e$  cost of purchased equipment  
 $a, b$  cost constants for the equipment  
 $S$  size parameter  
 $n$  exponent for that type of equipment

The size parameter of each piece of equipment relates to different scenarios described in Sect. "Scenario definition". The size of the dryer is measured by area (m<sup>2</sup>), the ball mill by capacity (t/h), and the rotary kiln by power (MW). The constants  $a, b, n$  are taken from [45] for the respective equipment. The area of the dryer is calculated using the dimensions given by [46] for different capacities. However, inaccuracies might occur in these calculations due to the ambiguity of the provided data on the dryer area. Ball mill capacities (t/h) for pd-AAC feedstock and clinker are taken from mass balances (Fig. 1) for different plant sizes. The energy requirement of the rotary kiln was calculated as the sum of the energy needed to heat the raw material to the reaction temperature ( $C_{p(\text{CaCO}_3)}=1 \text{ kJ/kg.K}$ ), reaction enthalpy for the decomposition of CaCO<sub>3</sub> ( $\Delta H_r(1000 \text{ }^\circ\text{C}) = 164.501 \text{ kJ/mol}$ ) and the formation of belite ( $\Delta H_r(1000 \text{ }^\circ\text{C}) = -93.911 \text{ kJ/mol}$ ). Since the flue gas and the hot clinker both contain sensible heat, 60% recovery efficiency was assumed for the flue gas and the clinker cooler, which reduces the net energy demand. However, a factor of 1.5 was applied to the net energy demand to account for inefficiencies such as heat losses through the walls of the kiln. In conventional OPC cement production, an increase in energy demand is typically estimated using a factor of 1.2 for the rotary kilns fired using fuel due to heat loss through the wall [19]. Since no data are currently available on the efficiency of electrically heated

kilns used for belite clinker formation, and such plants based on recycled raw materials as feedstock would be smaller in size compared to OPC plants, a conservative factor of 1.5 was assumed. Unlike the rotary kiln used for OPC production, that relies on fuel consumption, the kiln used for the production of RC-BCC is assumed to be heated indirectly by electricity. Therefore, the energy requirement for the rotary kiln is expressed in kWh/t.

Clinker cooling equipment cannot be considered in this study due to a lack of data. RC-BCC for lab kilns shows an agglomerate size of up to 2 mm, which is different from ordinary Portland cement clinker. Thus, specific cooling technology and setups have to be investigated in the future.

Finally, the Chemical Engineering Plant Cost Index (CEPCI) is used to adjust the equipment costs for inflation over time. Aspen Plus 12.1 version [47] is used to estimate the electricity requirements for the ball mill and dryer across different capacities.

Annual fixed costs resulting from the fixed-capital investment are calculated using an annuity factor that is calculated using Eq. (2) [48]. Annual fixed costs from the working capital and land costs are calculated using the interest rate per year, not the annuity, as no amortisation is needed in these categories. Future variations in interest rates are addressed through a sensitivity analysis described in Sect. "Sensitivity analysis".

$$\text{annuity factor} = \frac{i * (1 + i)^n}{(1 + i)^n - 1} \quad (2)$$

$i$  interest rate per year

$n$  service life of the plant in years

Overhead costs and general expenses are calculated as percentages of operating labour costs and total product costs. Transport of input material to the recycling plant and final products to the point of demand are not included in the economic consideration since the focus is on assessing the recycling plant itself. A brownfield investment is assumed since it could be added to existing infrastructure for construction and demolition waste treatment or AAC/cement production plants. A recycling plant at a greenfield location could double the brownfield investment [44]. Conventional cement plants typically operate for ~ 330 days per year, while the remaining days are planned for shutdowns and maintenance work [49]. However, as there is currently no plant operating on a continuous scale for producing belite from secondary feedstock (pd-AAC), the assumption of 275 working days was made to account for the uncertain feedstock availability and necessary maintenance. All relevant primary data and assumptions for the economic assessment are given in Table 1. For all input data not based on explicit assumptions, high-quality statistics or an expert interview were used as primary sources. For the price of CaCl<sub>2</sub>, however, no peer-reviewed or industry data were available. Therefore, online portals were used as the best accessible source.

## Scenario Definition

The size of a plant usually significantly impacts the total product costs. Therefore, different plant sizes are considered in scenarios to disclose the range of the total costs. The recycling plant has an input capacity of 50,000 t/a in the baseline scenario. It would need 14 of these

recycling plants to handle the current German pd-AAC amount of around 700,000 t/a and 40 to handle the expected increase of up to 2,000,000 t/a until 2050 (Sect. "Pd-AAC supply and revenue for the final product"). Moreover, other recycling plants with lower input capacity (10,000/25,000 t/a) are investigated to reflect more decentralised recycling possibilities where transport can be minimised. Additionally, recycling plant scenarios with higher input capacity (100,000/250,000 t/a) are included in calculating total costs when significant economies of scale become effective. The varying capacity in the different scenarios influences the required capacity of the machines. Generally, the change in equipment costs due to increased or reduced capacity can be calculated using Eq. (3) [54].

$$C_2 = C_1 * \left( \frac{Q_2}{Q_1} \right)^x \quad (3)$$

$C_2$  cost of capacity  $Q_2$

$C_1$  cost of capacity  $Q_1$

$x$  cost-capacity factor

Equation (3) is also used for scaling the electricity inputs of the machines since the electricity inputs are assumed to follow the same sublinear relationship with the capacity as the costs. Factor  $x$  is calculated separately for costs and electricity input (electricity-capacity factor). There are various suggestions for cost-capacity factors for different plants, machines, and machine parts in the literature. However, calculating the factor for every machine directly from specific cost and electricity input data is the most precise approach. Thus, machines' prices and electricity inputs were researched for two to six capacities. Rearranging Eq. (3) allows a calculation of machine-specific cost-capacity factors resulting in 0.37 for the crushers, 0.42 for the air separator, 0.5 for the NIR sorting machine, 0.2 for the compressed air generator, and 0.61 for the vibrating screen. The electricity-capacity factors are calculated the same way resulting in 0.82 for the crushers, 0.68 for the air separator, 0.55 for the NIR sorting machine, 0.64 for the compressed air generator, and 0.65 for the vibrating screen. It's assumed that all machines reach the highest capacity of 250,000 t/a (around 70 t/h), except for the NIR sorting machine. A direct manufacturer enquiry disclosed a maximum capacity of available NIR sorting machines of about 15 t/h for pd-AAC with an assumed density of 0.5 t/m<sup>3</sup> after primary crushing (<80 mm). Higher throughputs are supposed to be handled by parallel sorting on multiple NIR machines. However, one NIR sorting machine can take the pd-AAC input of up to 50,000 t/a. The parallel use of several machines is only relevant for the plant size scenarios of 100,000 t/a (two NIR sorting machines required) and 250,000 t/a (five NIR sorting machines required). Equation (3) is used for cost calculation of jaw crushing, impact crushing, air separation, NIR sorting, vibrating screen, and compressed air generation. The cost calculation of the dryer for the highest capacities, i.e., 100,000 and 250,000 t/a, is also performed using Eq. (3), as the dimension data was not given in the reference. The ball mill and rotary kiln costs in all scenarios are calculated equally to the baseline scenario.

## Results

This section shows the results of the economic assessment. First, the costs of mechanical pd-AAC processing and RC-BCC production are calculated for the considered scenarios (Sect. "Costs of mechanical pd-AAC processing and RC-BCC production"). Then, a sensitivity analysis of the results is presented (Sect. Sensitivity analysis).

### Costs of Mechanical pd-AAC Processing and RC-BCC Production

The recycling process, including mechanical processing and RC-BCC production, uses equipment described in Sect. "Mechanical pd-AAC processing" and Fig. 1. Table 2 discloses the costs and the electricity demand for the entire equipment of both recycling steps. The values for the conveyor belts reflect nine belts for the mechanical pd-AAC processing and eight belts for the RC-BCC production, one between all components of the recycling plant and all materials sorted out (one belt per material flow/arrow in Fig. 1). The conveyor belts are always needed for material transport. Therefore, no scaling of costs or electricity demand is performed for recycling plants of different capacities. The total costs of all equipment are then used as input for the total capital investment assessment (Table 3) following the method described in Sect. "Methodology of the economic assessment". The total capital investment is around 4 M€ for the mechanical pd-AAC processing and an additional 13.6 M€ for the RC-BCC production in a plant with a pd-AAC input capacity of 50,000 t/a.

The results of the total product cost calculation for the baseline scenario are presented in Table 4. The variable costs do not consider all aspects mentioned by [44] since the following are not associated with any charges in the case of mechanical pd-AAC processing and RC-BCC production: costs for fuel (as only electricity is used), refrigeration, steam, process water, cooling water, and royalties. Additionally, there are no raw material costs for the mechanical pd-AAC processing. Potential acceptance fees for the pd-AAC treatment are considered in comparing recycling and landfilling costs. However, raw material costs for limestone for the RC-BCC production are included (Table 1). The assessment of operating labour costs is calculated from data on operating labour requirements [44], assuming a

**Table 2** Equipment costs and electricity demand for mechanical pd-AAC processing and RC-BCC production in the baseline scenario (50,000 t pd-AAC/a)

equipment	equipment costs [€]	electricity demand [kWh/t input]
jaw crusher	59,422	1.4
impact crusher	43,110	2.7
air separator	52,035	1.0
NIR sorting machine	388,755	1.0
compressed air generation	9,981	0.3
vibrating screen	26,571	0.1
conveyor belts	131,400	0.1
<i>total for mechanical processing</i>	<b>711,274</b>	<b>6.7</b>
dryer	374,154	476.1
ball mill 1	615,709	14.6
rotary kiln	894,353	1398.3 kWh/t fines
ball mill 2	794,756	24.5
conveyor belts	102,200	0.3
<i>total for RC-BCC production</i>	<b>2,781,171</b>	<b>1447.7</b>

**Table 3** Capital investment calculation for the mechanical pd-AAC processing and RC-BCC production in the baseline scenario (50,000 t pd-AAC/a) based on the percentage of delivered equipment cost method by 41 [44]

cost category	percentage of delivered equipment	costs mechanical processing [€]	costs RC-BCC production [€]
<i>direct costs</i>			
purchased equipment delivered	n.a.	711,274	2,781,171
purchased-equipment installation	0.45	320,074	1,251,527
instrumentation and controls (installed)	0.18	128,029	500,611
pipng (installed)	0.16	113,804	444,987
electrical systems (installed)	0.1	71,127	278,117
buildings (including services)	0.25	177,819	695,293
yard improvements	0.15	106,691	417,176
service facilities (installed)	0.4	284,510	1,112,469
<i>total direct plant costs</i>	<b>2.69</b>	<b>1,913,328</b>	<b>7,481,351</b>
<i>indirect costs</i>			
engineering and supervision	0.33	234,721	917,787
construction expenses	0.39	277,397	1,084,657
legal expenses	0.04	28,451	111,247
contractor's fee	0.17	120,917	472,799
contingency	0.35	248,946	973,410
<i>total indirect plant costs</i>	<b>1.28</b>	<b>910,431</b>	<b>3,559,899</b>
<i>total costs</i>			
fixed-capital investment	3.97	2,823,760	11,041,251
working capital	0.70	497,892	1,946,820
land costs	n.a.	634,800	634,800
<i>total capital investment</i>	<b>n.a.</b>	<b>3,956,452</b>	<b>13,622,871</b>

highly automated process with two process steps (sorting, crushing/grading) for mechanical pd-AAC processing and three steps (drying, clinkerisation, milling) for RC-BCC production. The operating labour requirement is then multiplied by average labour costs (Table 1) to get total operating labour costs. Electricity costs are determined from the electricity demand (Table 2) and costs per kWh (Table 1). Waste treatment and disposal costs are calculated from treatment costs (Table 1) multiplied by the assumed 1% of all inputs to be sorted out. Additionally, CO<sub>2</sub> certificate costs must be considered for the RC-BCC production, as the cement industry has to buy certificates for the direct emissions. The CO<sub>2</sub> emissions of the process [43] are multiplied by current certificate prices (Table 1). Costs for operating supervision, maintenance and repairs, operating supplies, and laboratory charges are calculated from operating labour costs and fixed-capital investment using percentages given by [44]. Finally, costs for catalysts and solvents, including CaCl<sub>2</sub> needed as mineraliser in the RC-BCC production, are calculated using the input mass (Fig. 1) and CaCl<sub>2</sub> costs (Table 1).

The annuity is the central influencing aspect of fixed costs. It is determined by the annuity factor (Table 1) multiplied by fixed-capital investment (Table 3). The interest for working capital (Table 3) is considered separately. The interest rate (Table 1), not the annuity

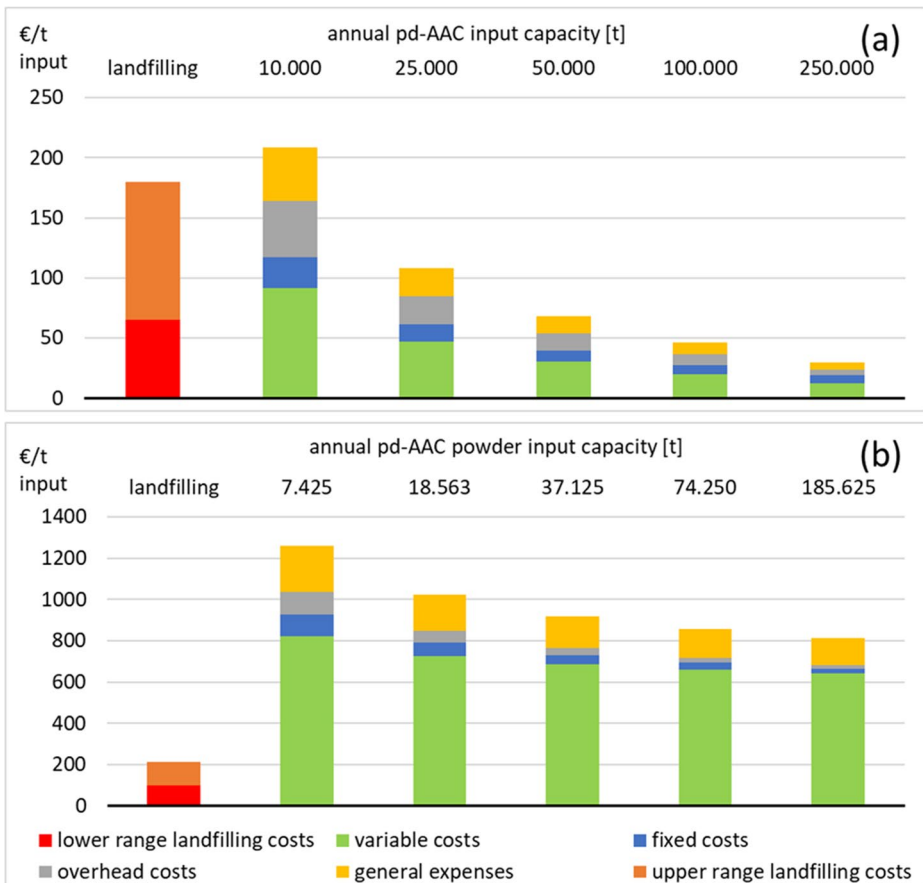
**Table 4** Product cost calculation for a pd-AAC recycling plant in the baseline scenario (50,000 t pd-AAC/a)

cost category	costs mechanical processing [€/t input pd-AAC]	costs RC-BCC production [€/t input pd-AAC]	reference
<i>variable costs</i>			
raw materials	0.00	55.35	own modelling
operating labour	17.51	32.59	own calculation (based on Peters et al., 2003)
operating supervision	2.63	4.89	0.15*operating labour (Peters et al., 2003)
electricity	1.78	507.15	own modelling
waste treatment and disposal	1.00	50.72	own modelling
maintenance and repairs	3.95	20.82	0.07*fixed-capital investment (Peters et al., 2003)
operating supplies	0.59	3.12	0.15*maintenance and repairs (Peters et al., 2003)
laboratory charges	2.63	4.89	0.15*operating labour (Peters et al., 2003)
catalysts and solvents	0.00	5.15	own modelling
<i>total variable costs</i>	<b>30.10</b>	<b>684.69</b>	
<i>fixed costs</i>			
annuity	6.20	32.65	0.11*fixed-capital investment (own calculation)
interest for working capital and land costs	1.59	4.87	0.07*(working capital+land costs) (own calculation)
taxes (property)	1.13	5.95	0.02*fixed-capital investment (Peters et al., 2003)
insurance	0.56	2.97	0.01*fixed-capital investment (Peters et al., 2003)
<i>total fixed costs</i>	<b>9.48</b>	<b>46.44</b>	
<i>overhead costs</i>	<b>14.46</b>	<b>34.98</b>	0.6*(operating labour+supervision+maintenance) (Peters et al., 2003)
<i>general expenses</i>			
administrative expenses	3.50	6.52	0.2*operating labour (Peters et al., 2003)
distribution and marketing expenses	7.53	101.18	0.11*total product costs (Peters et al., 2003)
research and development	3.42	45.99	0.05*total product costs (Peters et al., 2003)
<i>total general expenses</i>	<b>14.46</b>	<b>153.69</b>	
<i>total costs</i>	<b>68.50</b>	<b>919.80</b>	

factor, is used for calculation because the working capital is not amortised. Additionally, taxes and insurance are considered as a percentage of the fixed-capital investment given by [44]. Similarly, overhead costs and all general expenses are calculated from fixed factors of a base value specified in Table 4. The overhead costs include various aspects, such as medical, safety and protection, packaging, and storage facilities. The general administrative expenses include executive salaries, legal costs, office maintenance, and communications. Adding up the variable, fixed, overhead, and general expenses leads to the total product costs. These amount to around 69 €/t input for the mechanical processing and an additional 920 €/t input for the RC-BCC production in the baseline scenario.

The product costs are calculated similarly for all other scenarios (Supporting Information S1). These scenarios include mechanical processing with a 10,000 t/a to 250,000 t/a capacity. The RC-BCC production capacities correspond to around 74% of the mechanical processing input (Fig. 1), leading to scenarios with 7,425 t/a to 185,625 t/a pd-AAC powder input. Figure 2 shows all scenarios' total mechanical processing and RC-BCC production costs. The total product costs highly depend on the capacity of the recycling plant. The smallest plant of 10,000 t/a treats the pd-AAC with costs of around 209 €/t input for mechanical processing and around 1250 €/t input for RC-BCC production. The larger the plant, the lower the total costs, reaching approximately 30 €/t input for mechanical processing and an additional 800 €/t input for RC-BCC production in the scenario with the largest capacity. Due to the limestone input, the RC-BCC production can produce 1.71 t RC-BCC per t pd-AAC input. Thus, the total costs of the combined mechanical processing and RC-BCC production would be 493 €/t RC-BCC in the scenario with the highest capacity. Detailed results for all scenarios are given in Supporting Information S1.

The variable costs account for the largest share of the total costs, just below 50% of the total costs for mechanical processing and more than 50% for the energy-intensive RC-BCC



**Fig. 2** Total costs of mechanical pd-AAC processing (a) and RC-BCC production (b) and their composition for all considered recycling plant capacities (data can be found in Supporting Information S1)

production, reaching nearly 80% in large-capacity scenarios. Overhead costs and general expenses contribute around 20% each to the total costs of the mechanical processing. In comparison, general expenses (just below 20%) are higher than overhead costs (10% for small capacities, <5% for large capacities) for the RC-BCC production. Moreover, the fixed costs account for only about 10% (in scenarios with lower capacity) to 20% (in scenarios with higher capacity) of the total costs for mechanical processing. The fixed costs nearly equal the overhead costs for the RC-BCC production (10% for small capacities, <5% for large capacities).

These total pd-AAC recycling costs can be compared to pd-AAC landfilling costs of 65–180 €/t (Sect. "[Pd-AAC supply and revenue for the final product](#)"). The mechanical processing's total costs are nearly equal to the average landfilling costs for a recycling plant with 25,000 t/a input capacity. Total costs in higher-capacity scenarios are well below the landfilling costs. Thus, mechanical pd-AAC recycling is economically desirable, even without considering sale prices of around 5–15 €/t (Sect. "[Pd-AAC supply and revenue for the final product](#)"). However, the additional RC-BCC production is costly. Thus, total costs are significantly higher than landfilling costs. Cement sales prices of around 150 €/t (Sect. "[Pd-AAC supply and revenue for the final product](#)") are not sufficient to reach an economic break-even. A pd-AAC recycling plant of 250,000 t/a input capacity would have total costs for mechanical processing and subsequent RC-BCC production of nearly 850 €/t pd-AAC powder (nearly 500 €/t RC-BCC). Thus, the RC-BCC would need to generate a sales price of around 430€/t so the recycling process's costs would not exceed landfilling costs.

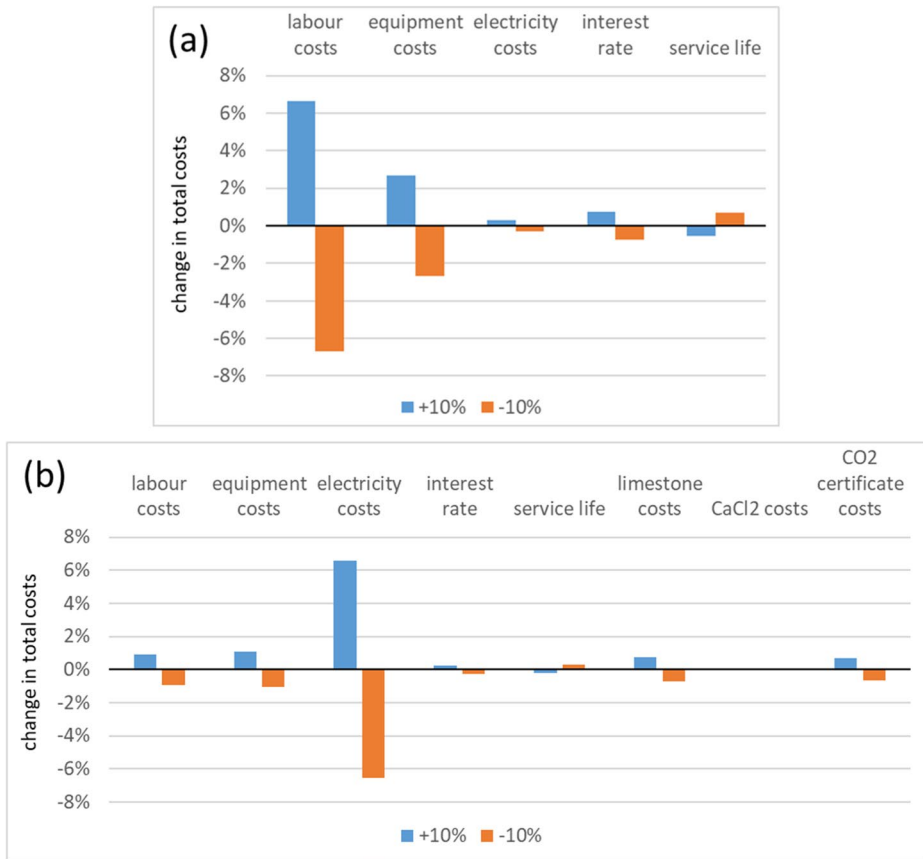
## Sensitivity Analysis

A sensitivity analysis was performed to determine the variation in total costs when input parameters change. The sensitivity analysis for both recycling steps includes the labour costs, equipment costs, electricity costs, interest rate, and recycling plant service life. Additionally, the limestone costs, CaCl<sub>2</sub> costs, and CO<sub>2</sub> certificate costs are varied for the RC-BCC production. All parameters are changed by ±10%, and the resulting changes in total costs are compared (Fig. 3).

The mechanical pd-AAC processing's total costs show the highest variability when changing labour costs (±6.7%) or equipment costs (±2.7%). In contrast, varying the electricity costs does not significantly influence the total costs (<1% change) as the mechanical processing is not very energy-intensive. The interest rate and the service life of the recycling plant also only show a minor influence on the total costs (<1% change).

In contrast, RC-BCC production is very energy-intensive, and electricity costs account for the largest share of the total costs. Therefore, varying the electricity costs leads to a significant change in total costs (±6.6%). All other parameters show much lower effects on the total costs of around ±1% for labour and equipment costs and even <1% for interest rate, service life, limestone costs, CaCl<sub>2</sub> costs, and CO<sub>2</sub> certificate costs. Variations in the CaCl<sub>2</sub> price have a negligible influence on the overall results, confirming that using a less robust data source in this case does not affect the conclusions.

Moreover, impurity levels are subject to uncertainties and, therefore, included in a scenario analysis. Besides the baseline (1% impurities), increased contamination (2% impurities), and heavy contamination (5% impurities) is considered (Table 5). Results show that the total costs increase as more material is sorted out and landfilled. In relative terms, the



**Fig. 3** Sensitivity analysis of total costs of (a) mechanical pd-AAC processing and (b) RC-BCC production

**Table 5** Changes on mechanical pd-AAC processing costs for different impurity levels

input capacity	10,000 t/a	25,000 t/a	50,000 t/a	100,000 t/a	250,000 t/a
total costs [/t input], 1% impurities	208.6 €	108.0 €	68.5 €	46.1 €	29.8 €
total costs [/t input], 2% impurities	209.8 €	109.1 €	69.7 €	47.3 €	31.0 €
total costs [/t input], 5% impurities	213.2 €	112.6 €	73.2 €	50.8 €	34.5 €

cost increase between 1% and 5% impurity level is highest for an input capacity of 250,000 t/a, summing up to 16%. In addition, the product yield in the scenarios falls from 99% to 98% and 95% respectively.

## Discussion

First, the regionally varying pd-AAC landfilling costs of 65–180 €/t impact the overall comparison and conclusion of whether pd-AAC recycling is economically viable. The landfilling costs differ significantly between countries and regions. Therefore, landfilling pd-AAC could be economically more attractive than recycling in areas with low pd-AAC landfilling costs. On the other hand, pd-AAC recycling in small plants, potentially even including RC-BCC production, can be economically viable in regions with very high landfilling costs.

The equipment electricity demand was identified through product data sheets and calculations, but not measured from an actual recycling plant. Generally, a conservative estimate was performed. The analysis does not consider, for example, the lower strength of AAC compared to other mineral building materials. Thus, in practice, the electricity demand will probably be well below the calculated values in this study, especially for the crushing and milling steps [42]. confirm this impression by giving specific jaw-crushing energy for AAC below the assumed electricity demand in this study. This observation is probably also valid for other processing steps. However, the dryer and the rotary kiln dominate the total electricity demand, while the electricity demand for mechanical processing is low.

Electricity costs are critical for the total costs of the RC-BCC production as they account for more than 50% of the total costs in the baseline scenario (input capacity of 50,000 t pd AAC/a). Potential mitigation measures include the procurement of renewable electricity, either from the grid or through on-site generation (e.g., photovoltaic systems), and the recovery and use of waste heat from other industrial processes for drying stages. These strategies could substantially reduce operational costs and greenhouse gas emissions and improve the economic and environmental performance of pd-AAC recycling and subsequent RC-BCC production.

Limitations of this study mainly include data availability and quality, as pd-AAC recycling is not yet established. Thus, pd-AAC recycling plants do not exist yet, and there is no field data on the different cost aspects. The study uses newly researched costs and electricity demands of recycling equipment and combines them with literature data to assess all relevant cost aspects. For example, the operating labour requirement strongly influences the variable costs and, thus, the total costs, especially for mechanical processing (Sect. "Sensitivity analysis"). However, the requirement is determined by an estimation based on [44], not a measurement in recycling plants for pd-AAC or similar products.

Moreover, the exclusion of transport costs is a limitation of the present study. This exclusion may be particularly relevant for decentralised recycling plants, potentially leading to an overestimation of economic feasibility in regions with long transport distances. Therefore, future work should integrate transport costs into the economic framework developed in this study. A promising approach is the optimisation of recycling networks, in which transport costs are explicitly balanced against economies of scale of centralised processing plants to provide a more realistic assessment of regional recycling strategies.

Furthermore, the assumed processing steps and respective equipment must be tested on this scale in practical trials to determine their suitability for pd-AAC recycling and RC-BCC production. It has to be verified if the processes and equipment for purifying the input material are sufficient to reach the desired final product quality. Moreover, it might influence the shares of pd-AAC granulate and powder produced. Furthermore, the impurities can vary substantially from the 1% assumed in this study. Higher percentages would increase the

costs of waste treatment and disposal (part of the variable costs) and reduce potential sale revenues for the final product per ton input, as a lower amount of the final product is produced. However, the influence of these aspects on the total costs is limited. One additional per cent of impurities in the input would increase the waste treatment and disposal costs by 1 €/t input. Overall, this study is the first approach to assess pd-AAC recycling economically. The results could be subject to noticeable changes when pd-AAC recycling is implemented in practice.

The existing knowledge about the technology used is also limited in terms of RC-BCC production. In particular, scaling the process to large input streams might lead to a change in technology. The limit of the currently proposed technology for the RC-BCC production, especially the electrically heated rotary kiln, has not yet been determined in practical trials. The rotary kiln might need to be fired by other technologies in large-capacity scenarios. Oxyfuel technology (natural gas combustion in pure oxygen) could be an option, but would slightly increase the energy demand as additional energy is needed for oxygen generation. Overall, there is a need for further technology development.

Moreover, the clinker cooling as part of the RC-BCC production was not integrated into the cost calculation. As mentioned above, the exact cooling technology remains uncertain. An estimated 10% of additional equipment costs would emerge based on the cooler cost in an ordinary Portland cement plant [55]. However, the sensitivity analysis (Sect. "Sensitivity analysis") shows that a 10% increase in equipment costs would increase the total product costs of the RC-BCC production by only around 1%.

## Conclusion

This study modelled a pd-AAC recycling plant, including mechanical processing and RC-BCC production from pd-AAC for different input capacity scenarios to calculate total costs for pd-AAC recycling. Results show significant economies of scale for the recycling plant. Total costs for mechanical processing vary between 209 €/t input for the smallest plant of 10,000 t/a and 30 €/t input for the largest plant of 250,000 t/a. A subsequent RC-BCC production would incur additional costs between 800 €/t input (largest plant) and 1250 €/t input (smallest plant). Overall, production costs for RC-BCC are around 500 €/t, so minimum sales prices of about 430 €/t would be necessary to reach average pd-AAC landfilling costs. However, the recycling products from mechanical pd-AAC processing can also be used for different recycling purposes. The minimum capacity of the recycling plant needs to be around 50,000 t/a input for the total recycling costs to be lower than the lower range of pd-AAC landfilling costs of 65–180 €/t. Plants with higher capacities could even mechanically treat the pd-AAC for costs well below the landfilling. In conclusion, this study indicates that pd-AAC recycling can be economically beneficial compared to landfilling and, thus, should be fostered.

In addition to the economic assessment results, environmental assessment shows that pd-AAC recycling also reduces greenhouse gas emissions compared to landfilling by up to 0.5 kg CO<sub>2</sub> eq./kg pd-AAC [37]. RC-BCC production from AAC using renewable electricity can even reach reductions of up to 0.77 kg CO<sub>2</sub> eq./kg pd-AAC [43]. This environmental assessment underlines the benefit of pd-AAC recycling.

Increasing pd-AAC volumes in the following decades will further extend the economic advantage of pd-AAC recycling, as high recycling plants' capacities lead to significant reductions in total costs. Moreover, landfilling costs are most likely to increase significantly in future. However, the legal framework for pd-AAC recycling can still be improved. For example, regional modifications in the legislation complicate recycling.

Future research should enhance the data availability to assess pd-AAC recycling, for example, by providing data from pilot plants to improve the quality of this economic assessment further. The proposed model is intended as a benchmark framework. By substituting country-specific parameters (e.g., interest rates, labour costs, energy costs, landfill fees), it can be applied to other regional contexts. Additionally, location and logistics planning will be essential to advance pd-AAC recycling. Regional differences in pd-AAC volumes, demand, and landfilling fees can significantly influence the establishment of an AAC recycling network. Moreover, transport costs presumably impact the total recycling costs, making logistics planning vital. Thus, future research should investigate logistics optimisation. Potential approaches include hub-and-spoke models, in which demolition material is collected at centralised hubs before processing or redistribution. Furthermore, optimisation algorithms, such as linear programming can be used to minimise variable costs, fixed costs, and transport costs under given constraints.

**Supplementary Information** The online version contains supplementary material available at <https://doi.org/10.1007/s43615-026-00796-4>.

**Funding** Open Access funding enabled and organized by Projekt DEAL. This work was supported by the Federal Ministry of Education and Research (BMBF) Germany within the research project REPOST [grant number: 033R249B]. The responsibility for the content of this publication lies with the authors.

**Data Availability** 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.

## Declarations

**Conflict of interest** The authors declare no conflict of interest.

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