POST-DEMOLITION AUTOCLAVED AERATED CONCRETE: RECYCLING OPTIONS AND VOLUME PREDICTION IN EUROPE

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ABSTRACT

Autoclaved aerated concrete (AAC) is an increasingly used building material due to its exceptional thermal properties. Post-demolition AAC is mainly disposed in landfills because of lacking established recycling processes. However, the growing demand for sustainable products, greenhouse gas reduction, decreasing landfill capacities and new legal frameworks require recycling options for post-demolition AAC.

Current research includes using post-demolition AAC recycling in the production of lightweight aggregate concrete, lightweight mortar, no-fines concrete, and floor screed. Even closed-loop recycling could be achieved by adding finely ground post-demolition AAC in the AAC production process or by producing belite cement clinker from post-demolition AAC as a substitution for Portland cement.

Predicting the generation of post-demolition AAC volumes is crucial for a recycling and circular management of AAC. But, post-demolition AAC volumes in Europe are currently neither recorded in statistics nor investigated in comprehensive studies. Therefore, a post-demolition AAC prediction model is presented that quantifies post-demolition AAC on a national and European level. Results show low volumes in South East, Western, and Southern Europe as well as Scandinavia due to small market sizes. In North West and Central Europe, especially the UK (700,000 m³) and Germany (1,200,000 m³) in 2020 drive post-demolition AAC volumes. The most significant post-demolition AAC volumes occur in Eastern Europe, especially in Poland (1,800,000 m³) and Russia (3,900,000 m³) in 2020. While relative volumes between the regions stay similar, the absolute post-demolition AAC volumes in Europe will nearly double in the next decade from 12.3 to 22.0 million m³.

Keywords: autoclaved aerated concrete; circular economy; material outflow analysis; post-demolition autoclaved aerated concrete; recycling

INTRODUCTION

Worldwide, resource consumption and CO_2 emissions are beyond a sustainable limit. Therefore, the UN aims at sustainable development goals like responsible consumption and production, climate action and sustainable cities [1]. Circular Economy plays an essential role to reach those goals – especially in the construction and demolition (C&D) sector, where substantial mass flows lead to high CO_2 emissions, energy and resource consumption and significant construction and demolition waste (C&DW) amounts. Worldwide, more than 3 billion tons of C&DW were generated in 2012 [2]. However, a considerable share of the potential of a circular economy remains unused [3].

Autoclaved aerated concrete (AAC) is produced from quartz sand, cement, quicklime, anhydrite, aluminium powder/paste (as aerating agent), and water. AAC has a porous structure, low density, and exceptional thermal insulation properties among mineral building materials. Therefore, AAC is popular for masonry units and mineral insulation boards, especially in residential buildings. And, construction and deconstruction processes of AAC require less effort than layered insulated materials (e.g. bricks with insulation) because AAC is a mono-material. This leads to time and cost savings in (de)construction processes and contributes to the high popularity of AAC. E.g. in Germany, the production of AAC began in 1950 [4], and in 2018, 23% (trending upwards) of the completed residential buildings were built using AAC [5].

AAC production waste or breakage is already recirculated. However, post-demolition AAC is not yet recycled because the porous structure, adhering substances, and small quantities of sulphate hamper high-quality recycling. Therefore, post-demolition AAC is mainly landfilled. However, decreasing landfill capacities and legal requirements – especially the European Waste Framework Directive 2008/98/EC – demand for AAC recycling. But, information on post-demolition AAC volumes is crucial to design and manage a circular supply chain for AAC. This study tries to fill the gap because only negligible information about recyclable AAC volumes in Europe is available as official statistics and comprehensive studies are lacking. First, a short overview of post-demolition AAC recycling options is provided. Then, expected post-demolition AAC volumes in Europe are quantified based on historic AAC production data, and building lifetime assumptions. Since comprehensive AAC production data is only available for Germany and the UK, post-demolition AAC volumes in other European countries and regions are predicted based on the current AAC market volume.

POST-DEMOLITION AAC RECYCLING OPTIONS IN LITERATURE

Reusing post-demolition AAC blocks is no practical possibility due to the need for an overly careful deconstruction process [6] and complex transportation and storage. However, crushed post-demolition AAC in fine powder or granulate form could be used in different recycling options. First, post-demolition AAC powder could be used in AAC production [7, 8] to establish a closed-loop recycling. However, only up to 20% of primary raw materials [7] or up to 50% of the sand [8] can be substituted by post-demolition AAC powder. Besides, belite cement clinker production from post-demolition AAC powder [9, 10] could handle significant amounts of post-demolition AAC, because it can be used as primary raw material in many applications such as AAC production (closed-loop recycling) or autoclaved sand-lime brick production (open-loop recycling).

Furthermore, various open-loop recycling options for post-demolition AAC are subject to current research. These options include the application of post-demolition AAC in light mortar [11], lightweight aggregate concrete [6, 11], floor screed [12], and no-fines concrete in the form of stumped concrete with decorative function or shuttering blocks [6]. Besides, there are suggestions for downcycling/utilisation options for post-demolition AAC like the use in phosphorus filters [13], fertilisers [14, 15] and landscaping [16].

Overall, promising recycling options for post-demolition AAC are presented in the literature. However, implementing a recycling network for these recycling options needs further knowledge on current and future post-demolition AAC volumes that can be expected.

POST-DEMOLITION AAC VOLUME PREDICTION IN EUROPE

Methodology

The European Waste Catalogue specifies different codes to record different types of waste. However, there is no AAC-specific code. In practice, post-demolition AAC is allocated to the codes 170101 (concrete), 170107 (mixtures of concrete, bricks, tiles, and ceramics) and 170802 (gypsum-based construction materials). Thus, no inferences about the post-demolition AAC volume are possible due to large volumes of different types of building rubble recorded in these codes. And, the literature on this topic is limited to stockpile studies, e.g. [17] and [18] for Germany, while comprehensive waste volume studies are missing. Therefore, [19] developed a model that predicts regional (NUTS 3 level) post-demolition AAC volumes in Germany based on AAC production, building lifetime assumptions, regional construction activity, and regional AAC popularity. This study uses the same methodology to determine current and future post-demolition AAC volumes in Europe, excluding regionality below the national level. Therefore, data on regional construction activity and regional AAC popularity are unnecessary. Building lifetime assumptions (for residential and non-residential buildings) are adopted from [19]. Residential and non-residential buildings are considered independently as they have different lifetimes. A triangular lifetime probability function with 35 and 95 years as lifetime boundaries and 65 years as the most probable lifetime is assumed for residential buildings. For non-residential buildings, a similar triangular lifetime probability function with lifetime boundaries of 15 and 100 years and a most probable lifetime of 40 years is assumed. The total post-demolition AAC volume from both building types is added up employing average shares of AAC used in residential and non-residential buildings. The share of AAC used in residential buildings is assumed to be 85.5% and 14.5% in non-residential buildings respectively following [19]. Overall, the post-demolition AAC volume in a country for a specific year is calculated based on these lifetime assumptions and national historic AAC production using the following equation:

$$pd\ AAC_{c,y} = \sum_{a=1}^{100} \big(AAC\ production_{c,y-a} * P_r(a) * 0.855 + AAC\ production_{c,y-a} * P_{nr}(a) * 0.145\big) \quad \text{(Eq. 1)}$$

$pd\ AAC_{c,y}$	post-demolition (pd) AAC volume in country c and year y [m³]
$AAC\ production_{c,y}$	AAC production volume in country c and year y [m³]
$P_r(a)$	probability of a residential building's (r) lifetime of a years [-]
$P_{nr}(a)$	probability of a non-residential building's (nr) lifetime of a years [-]

However, data availability differs between the European countries (Figure 1). Thus, there are three different post-demolition AAC prediction approaches based on data availability for every country (Figure 2).

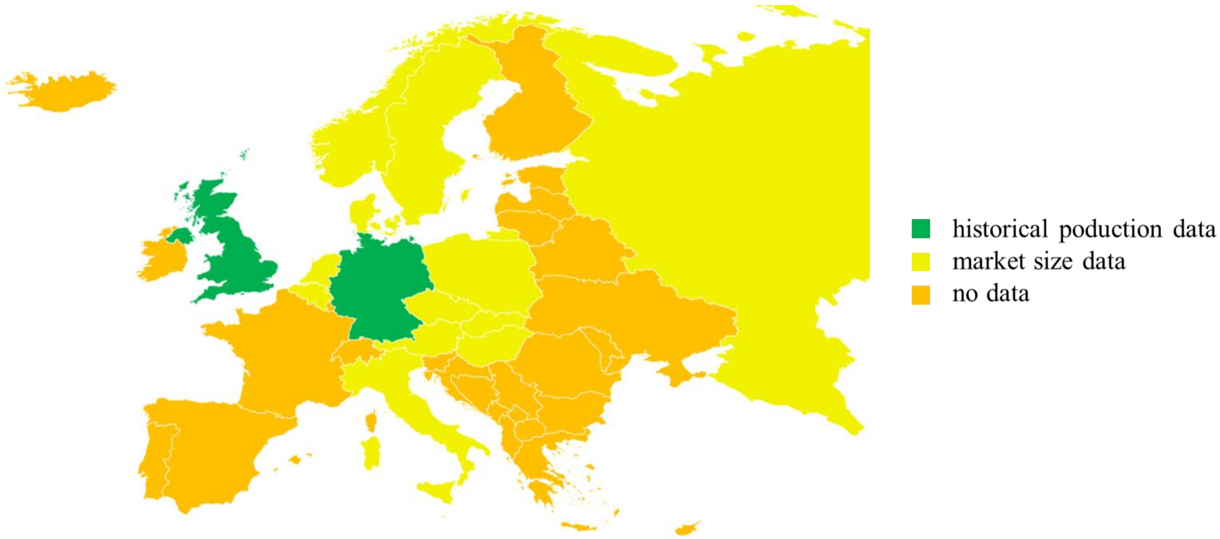

Figure 1. Data availability for post-demolition AAC prediction in the European countries

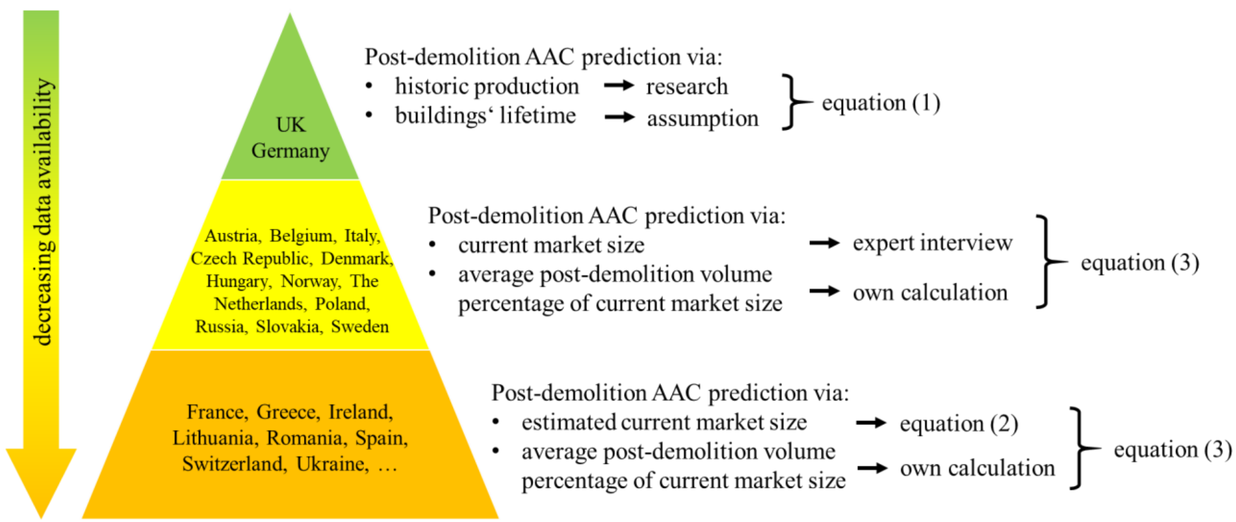

Figure 2. Different post-demolition AAC prediction approaches depending on national data availability

Comprehensive national AAC production data is only available for Germany [19] and the United Kingdom (direct inquiry to the UK Department for Business, Energy & Industrial Strategy). Therefore, for the other European countries another approach is developed: First, current AAC market sizes which reflect current production volumes are researched. Data is available for Austria, Belgium, Czech Republic, Denmark, Hungary, Italy, Norway, The Netherlands, Poland, Russia, Slovakia, and Sweden (expert interview: Dr. Oliver Kreft, Xella Technologie- und Forschungsgesellschaft mbH). Second, Europe is divided into different regions, and a representative country for every region is selected (Figure 3) to fill the data gap of the missing countries (countries with no data in Figure 1). All countries with missing market size data in a region are assumed to have the same AAC market size per population size as their representative country. So, the absolute market size is calculated via population data [20] using equation (2). This calculation allows an extension of the AAC market size estimation to whole Europe.

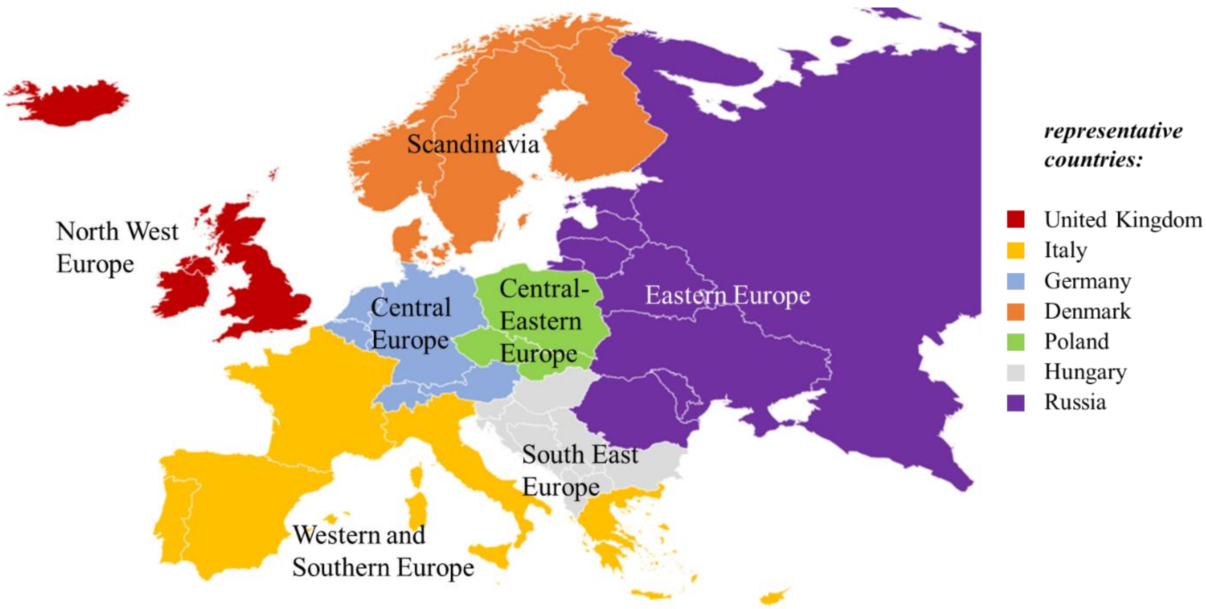

Figure 3. European regions and their representative countries used for post-demolition AAC prediction

$$AAC\ market_c = AAC\ market_{rep} * \frac{population_c}{population_{rep}} \qquad \text{(Eq. 2)}$$

$AAC\ market_c$	current AAC market size in country c [m³]
$AAC\ market_{rep}$	current AAC market size in representative country rep [m³]
$population_c$	population in country c [-]
$population_{rep}$	population in representative country rep [-]

Third, post-demolition AAC volumes have to be calculated for the countries where only current market size data or estimation is available. To do so, the average post-demolition AAC percentages of current production volumes in Germany and the UK are taken which show a similar increase in the following years. Therefore, it is assumed that the post-demolition AAC volume for every country equals a particular percentage of the current market size, depending on the year. Finally, post-demolition AAC volumes for every European country is calculated using the following equation:

$$pd\ AAC_{c,y} = AAC\ market_c * percentage_y \qquad \text{(Eq. 3)}$$

$pd\ AAC_{c,y}$	post-demolition (pd) AAC volume in country c and year y [m³]
$AAC\ market_c$	current AAC market size in country c [m³]
$percentage_y$	post-demolition AAC percentage of the current market size in year y [-]

Results

Post-demolition AAC volumes can be calculated for Germany and the UK using equation (1) because historical production data is available. In contrast to the German dataset (Figure 4 (a)), UK production data only goes back to 1967. Therefore, a linear increase for the period 1950 to 1966 is assumed (Figure 4 (b)). In our model, we calculated that significant post-demolition AAC volumes have occurred since the year 2000 in both countries (Figure 4). In the following years, calculated post-demolition AAC volumes increase sharply and constantly in both countries, exceeding 1 million m³ annually in 2018 (Germany) and in 2026 (UK) and reaching more than 4 million m³ in Germany and more than 2 million m³ in the UK in 2050. This rise would reach/exceed the AAC production in the UK/Germany if production volumes stay on today's level.

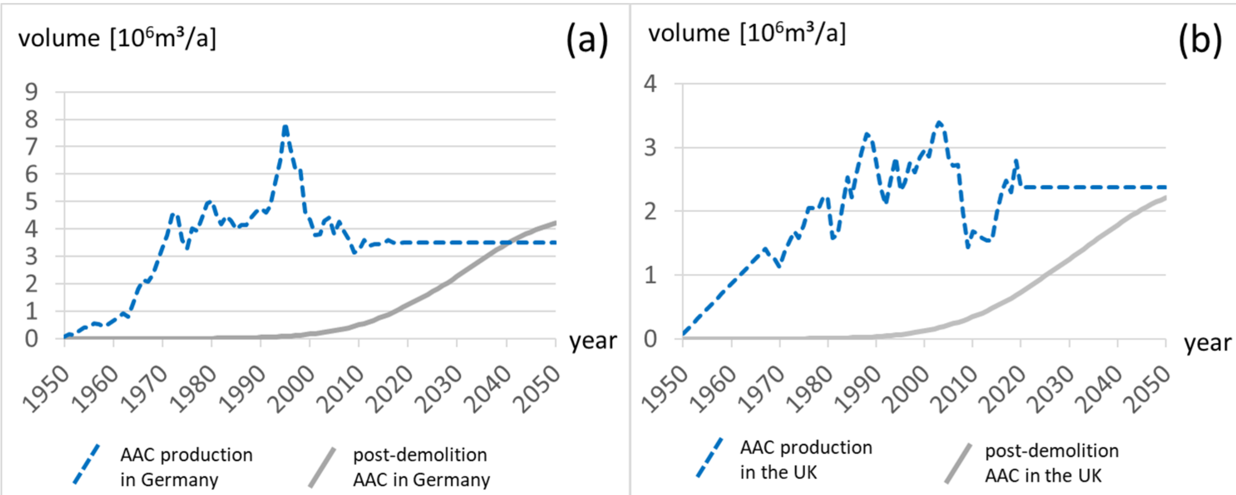

Figure 4. AAC production (dashed blue line) and post-demolition AAC (grey line) in Germany (a) and the UK (b)

The calculation of post-demolition AAC volumes for all other countries is based on current market sizes or market size estimations and the average post-demolition volume percentage of the current market size. The average percentage is determined for different years using the German and UK calculations calculated e.g. for 2020, 2025, and 2030 (Table I), where the German and the UK percentages are relatively close to each other. In the more distant future, they diverge more. The post-demolition AAC calculation (Table II, Figure 5) for 2020 shows relatively low volumes in South East Europe and Scandinavia, which can be explained by their small market sizes. Somewhat larger volumes can be found in the region Western and Southern Europe due to higher population and in North West Europe, where the UK alone accounts for 700,000 m³. In Central Europe, volumes are double the amount of North West Europe with the highest volume in Germany (1,200,000 m³). The most significant post-demolition volumes occur in Central-Eastern and Eastern Europe due to large markets in Poland and Russia. These two countries together (Poland: 1,800,000 m³, Russia: 3,900,000 m³) account for nearly half of the total European post-demolition AAC volume of around 12,290,000 m³ in 2020. A sharp increase of post-demolition AAC volumes throughout Europe is noticeable in the next decade. Absolute numbers nearly double in Europe from around 12.3 to 22.0 million m³ in only ten years. Increasing AAC production in the 60s, which is expected to reach its end of life around 2030, can explain this rise. However, the relative volumes between the regions stay similar in 2025 and 2030.

Table I: Post-demolition AAC volume percentage of the current market size

year	percentage Germany	percentage UK	average percentage
2020	35.2%	31.9%	33.5%
2025	49.2%	42.9%	46.0%
2030	65.2%	54.6%	59.9%

Table II: AAC market sizes and calculated post-demolition AAC volumes for 2020, 2025, and 2030 of all European countries (excluding small countries with less than 100,000 inhabitants)

country	(estimated*) market size [m³]	post-demolition AAC 2020 [m³]	post-demolition AAC 2025 [m³]	post-demolition AAC 2030 [m³]
Albania	79,885*	26,795	36,763	47,871
Austria	122,000	40,921	56,144	73,108
Belarus	751,782*	252,158	345,969	450,502
Belgium	330,000	110,687	151,866	197,751
Bosnia and Herzegovina	92,105*	30,893	42,387	55,193
Bulgaria	195,405*	65,541	89,925	117,095
Croatia	115,159*	38,626	52,996	69,008
Cyprus	12,651*	4,243	5,822	7,581
Czech Republic	1,160,000	389,080	533,831	695,124
Denmark	325,000	109,010	149,565	194,755
Estonia	105,216*	35,291	48,420	63,050
Finland	312,061*	104,670	143,610	187,001
France	696,788*	233,712	320,661	417,547
Germany	3,477,279	1,223,853	1,709,977	2,267,974
Greece	112,809*	37,838	51,915	67,601
Hungary	269,000	90,226	123,794	161,197
Iceland	11,500*	3,857	5,292	6,891
Ireland	164,442*	55,156	75,676	98,541
Italy	650,000	218,019	299,129	389,509
Latvia	153,331*	51,429	70,563	91,883
Lithuania	222,759*	74,717	102,514	133,487
Luxembourg	25,267*	8,475	11,628	15,141
Malta	4,707*	1,579	2,166	2,820
Moldova	322,249*	108,087	148,299	193,106
Montenegro	17,401*	5,837	8,008	10,428
Netherlands	410,000	137,520	188,682	245,690
North Macedonia	57,718*	19,359	26,562	34,587
Norway	17,000	5,702	7,823	10,187
Poland	5,400,000	1,811,235	2,485,074	3,235,923
Portugal	109,958*	36,881	50,602	65,892

Romania	1,551,282*	520,322	713,898	929,598
Russia	11,590,000	3,887,448	5,333,705	6,945,249
Serbia	243,923*	81,815	112,253	146,170
Slovakia	650,000	218,019	299,129	389,509
Slovenia	57,580*	19,313	26,498	34,504
Spain	500,609*	167,911	230,380	299,988
Sweden	106,000	35,554	48,781	63,520
Switzerland	356,663*	119,630	164,136	213,729
Ukraine	3,518,816*	1,180,260	1,619,355	2,108,633
United Kingdom	2,291,135	730,576	982,073	1,251,563

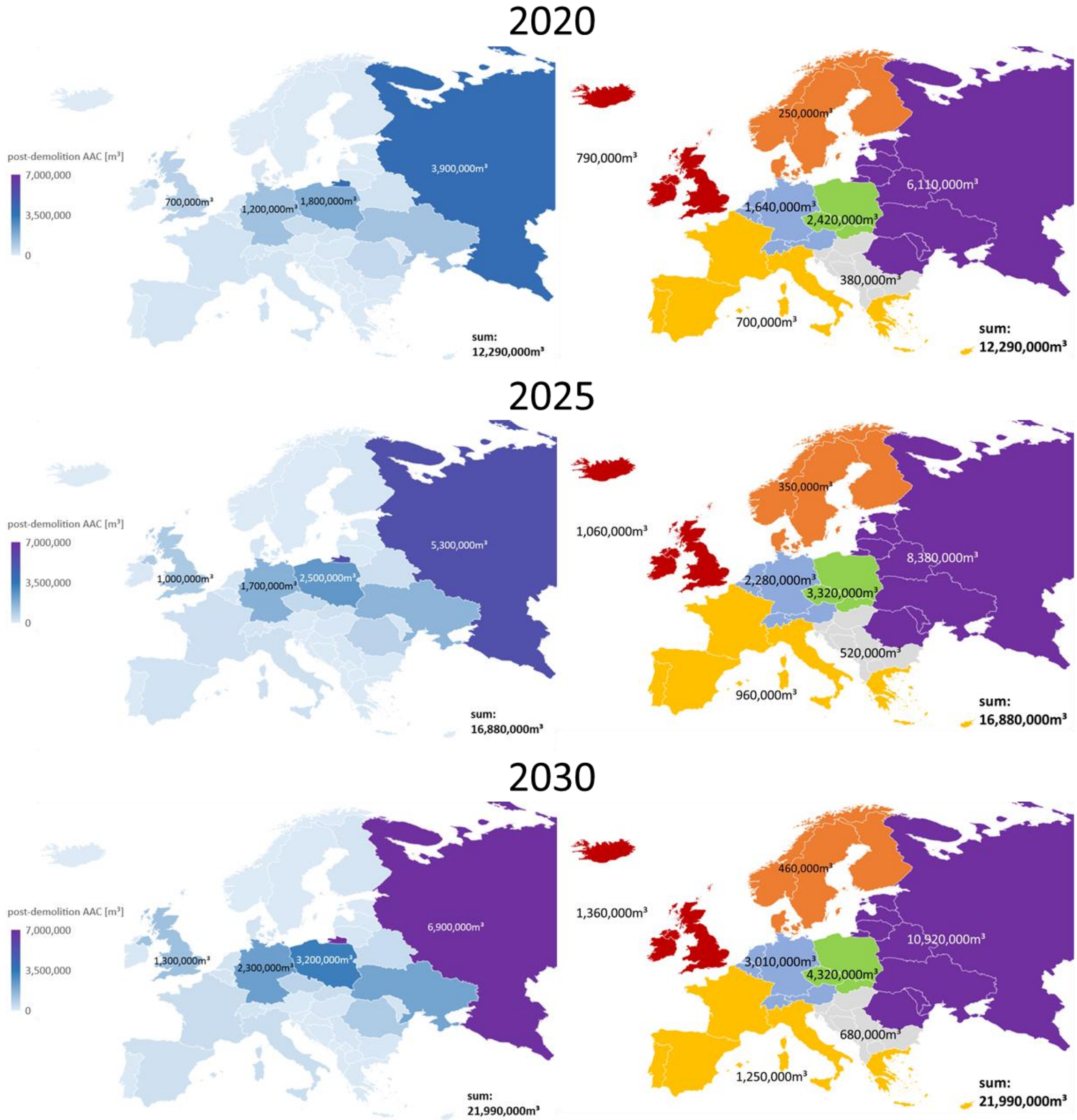

Figure 5. Post-demolition AAC volumes in Europe for 2020, 2025 and 2030

The average post-demolition volume percentage of the current market size has a great influence on the total European post-demolition AAC volume because it is used in the prediction for every country except for Germany and the UK. Therefore, a sensitivity analysis of European post-demolition AAC volumes with regard to this percentage is carried out (Table III). The analysis shows that a +/-10 %-point variation changes the total European post-demolition AAC volume by around 3 million m³. Thus, the post-demolition AAC volume could reach more than 15 million m³ in 2020 and even more than 25 million m³ in 2030.

Table III: Sensitivity analysis of European post-demolition (pd) AAC volume with regard to the post-demolition percentage of the current market size

year	percentage (baseline)	pd AAC volume [m³]	percentage (-10 %-points)	pd AAC volume [m³]	percentage (+10 %-points)	pd AAC volume [m³]
2020	33.5%	12,290,000	23.5%	9,200,000	43.5%	15,360,000
2025	46.0%	16,880,000	36.0%	13,790,000	56.0%	19,950,000
2030	59.9%	21,990,000	49.9%	18,900,000	69.9%	25,070,000

Limitations and Shortcomings

An essential component of the post-demolition AAC prediction is the assumption of lifetime functions for residential and non-residential buildings. However, the lifetime functions are based exclusively on literature values. Empirical data is not available. And, various building characteristics (e.g. monument conservation, building material, construction technique, floor plan, renovation) influence its lifetime fundamentally. Overall, the lifetime functions are subject to noticeable uncertainties.

Furthermore, comprehensive production data is scarce, so only post-demolition AAC volumes in Germany and the UK can be calculated using the basic approach. For all other countries, post-demolition AAC volume is calculated using the current market size's average post-demolition volume percentage. This percentage is calculated as the mean value of only two countries (Germany and the UK) and thus also associated with uncertainties. Besides, reliable data on the current market size is only available for some countries. The market size of the remaining countries has to be estimated. Generally, an AAC-specific waste code or AAC waste statistics are missing but could help to quantify the available post-demolition AAC volume for recycling. Furthermore, the used percentage represents the situation in the longer existing AAC markets of Germany and the UK while AAC markets especially in Southern and South East Europe may be much younger and used percentages are not suitable. A change would shift post-demolition AAC volumes into the future. In general, including comprehensive AAC production or market size data of the past would improve the prediction of the model.

CONCLUSION

A European prediction model was developed to assess future post-demolition AAC volumes at national level. In 2020, volumes are the largest in Russia (3,900,000 m³) and Poland (1,800,000 m³). In other regions, Germany (1,200,000 m³) and the UK (700,000 m³) account for the largest expected national post-demolition AAC volumes. Furthermore, post-demolition AAC volumes in Europe will increase considerably in the following decade from 12.3 to 22.0 million m³. Therefore, AAC recycling has to be fostered to avoid landfilling these volumes and eventually to substitute primary construction material.

Further research could focus on gathering data on AAC production and AAC market sizes for more European countries to improve the prediction quality. Furthermore, building lifetimes should be further investigated. Especially knowledge on the lifetimes of different AAC products would be interesting. The presented model can be transferred to other regions/continents and to other building materials like clay bricks, timber, sand-lime bricks, or lightweight concrete blocks. To do so, adaptions on production data and possibly building lifetimes are necessary.

ACKNOWLEDGEMENT

This work was supported by the Federal Ministry of Education and Research (BMBF) Germany within the research project REPOST [grant number: 033R249B]. We gratefully thank Xella Technologie- und Forschungsgesellschaft mbH (Dr. Oliver Kreft), and the United Kingdom Department for Business, Energy & Industrial Strategy (Oliver Wright) for the constructive support and for providing valuable data. The responsibility for the content of this publication lies with the authors.

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