Journal of Material Cycles and Waste Management (2022) 24:1432–1443
https://doi.org/10.1007/s10163-022-01406-9

SPECIAL FEATURE: REGIONAL CASE STUDY

Material Cycles in Construction Works

Circular economy for durable products and materials: the recycling of plastic building products in Germany—status quo, potentials and recommendations

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Received: 30 September 2021 / Accepted: 31 March 2022 / Published online: 28 April 2022

Abstract

The construction sector is the second largest area for the application for plastics. Due to the long life times of construction products, the implementation of the circular economy faces its own challenges. To investigate this challenge, the study covers a market study for Germany, voluntary take-back and recycling schemes of construction products, as well as the use of plastic recyclates in construction products. In addition, plastic packaging of construction products is covered. Opportunities and barriers to the use of recycled plastics in construction products are derived from the intersection of available technologies, recycle supply, and technical requirements for construction products. The report concludes with recommendations to various stakeholders on how to promote the use of recyclates in construction products and their packaging. Important points here are the introduction of a recycle quota for films as construction product packaging and the description of recycling possibilities and recycle content in the technical documentation of construction products.

Keywords Durability · Recyclability · Recycled content · Plastic building product · Construction

Abbreviations

AGPR	Working group on the recycling of PVC floor covering
e.g.	Example given
EAD	European assessment document
EPDM	Ethylene propylene diene monomer rubber
EPS	Expanded polystyrene
Fig	Figure
GRP	Glass fibre-reinforced plastic
hEN	Harmonised European standard for a construction product
i.e.	id est (latin for that is)
KRV	German plastic pipe industry association
kt	Kilo tons (mass of 10^9 g)
NBR	Nitrile butadiene rubber
ÖAKR	The austrian working group for plastic pipe recycling
PA	Polyamide
PA6	Polyamide—polycaprolactam, nylon 6
PE	Polyethylene
PET	Polyethylene terephthalate
PIR	Polyisocyanurate
PMMA	Polymethylmethacrylate
PP	Polypropylene
PS	Polystyrene
PUR	Polyurethane
PVB	Polyvinyl butyral
PVC	Polyvinyl chloride
PVC-P	Plasticized polyvinyl chloride
PVC-U	Unplasticized polyvinyl chloride
SBR	Styrene butadiene rubber
t	Tons (mass of 10^6 g)
XPS	Extruded polystyrene

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Introduction

The construction sector is the second largest application sector of plastics in Germany and the amount of plastics used in this sector is growing as well [1]. Only the packaging sector (4319 kt in 2019) uses more plastics annually. Construction (3583 kt in 2019) is followed by the automotive (1509 kt in 2019) and the electronics industries (881 kt in 2019). Use of plastics in the construction sector comes with some specificities: In contrast to other sectors, polyvinyl chloride (PVC) accounts for the largest margin of polymers being used. For insulation products polystyrene (PS) and polyurethane (PUR/PIR) prevail and further construction products are made of a diverse range of different polymers. Moreover, the material is being kept in a single product for a very long time, often decades, while other plastic applications have very short (packaging often with a couple of days or weeks) or medium (cars and electronics) product lifetime. The construction sector uses a wide variety of plastic products including windows, pipes, insulation, films and many more. This corresponds to a use of a diverse range of materials. Due to all these factors, it is extremely challenging to establish a high-value plastics recycling or even extended producer responsibility in the construction sector [2]. However, given the amount of plastics already in use here and the yearly growing rate of plastic use, a huge amount of these materials is amassing in the anthropogenic stock. In future, the necessity of a circular plastics economy sector increases which is put into a political plan by the European plastics strategy introducing and accelerating measures for recycling of construction products made of plastics [3].

The leading research question was, how high-value plastic recycling can be achieved in the construction sector in Germany. This was analysed based on the investigation of plastics products and plastics recycling in the construction sector. The study comprises an analysis of the sector-specific use of plastic products, the current situation of plastics recycling and developments towards a circular economy. Chapter two elaborates more profoundly on the characteristics and challenges of high-value plastic recycling in the construction sector and also portrays the specificities of plastics recycling for construction products in Germany. Chapter three delineates the methods used and the data gathered to substantiate the analysis. Chapter four presents and discusses the findings with regard to the research question and gives recommendations for different stakeholders. Necessary measures on the side of policy makers, opportunities for the plastics and recycling industries and needs for further research are addressed.

The role of high-value plastic recycling in a circular economy for the construction sector (theory)

Increasing recycling rates of plastic products is essential to achieve environmental goals such as improving resource efficiency, minimising marine litter and reducing greenhouse gas emissions. A successful approach for a valuable circular economy of plastics is the division into economic sectors, i.e. packaging, construction products, automotive and electronic devices and agricultural plastics [3]. Product regulations as well as waste regulations are sector specific and determine the requirements for manufacturers, products and waste treatment. In Germany, plastic wastes of packaging, automotive and electronic devices are covered by extended producer responsibility that lead to high valuable plastic recycling. Considering the advantages of these regulations, emphasis was put on the recycling of the second largest sector for plastics, construction products. It was explored how loops can be closed under the constraints of a sector, in which extended producer responsibility is neither economically fair nor ecologically appropriate [2]. Alternative concepts for a circular economy include standards for recyclability of construction products, waste management structures including selective dismantling, collection and treatment, and finally, complex requirements for the use of recycled plastics in construction products. Voluntary recycling schemes and best practices for the use of recycled materials were evaluated. New concepts and construction product specific challenges became visible.

One important issue for recycling is the sector-specific sorts of polymers, their different varieties and compounds. Typical plastics in the construction sector are unplasticized polyvinyl chloride (PVC-U) in profiles, doors, window frames and pipes, plasticized polyvinyl chloride (PVC-P) in floor- and roof-coverings, polystyrene and polyurethane in insulation materials, and finally bituminous materials. Apart from that, there are numerous kinds of plastics in different applications and partly small-scale products, such as fittings and anchors. This means, that recycling of construction products profoundly differs from recycling of plastic packaging, which is predominantly the recycling of polyethylene (PE), polypropylene (PP) and polyethylene terephthalate (PET). It requires selective dismantling and collection. Also the contaminants differ, mineral particles prevail, and the number of additives that have been regulated in the meanwhile of the products lifetime is high. As a consequence, recycling of plastic construction products is a demanding task for a low amount of waste and partly severely aged material.

Consequently, plastic recycling is of minor importance in the construction sector, so far. In Germany, waste of different plastic types is not separated and collected as mixed construction and demolition waste, which is simply separated into metals, minerals and plastic in treatment facilities, which do usually not include a polymer specific separation. For a polymer specific recycling, voluntary take-back schemes and specialized recycling technologies prevail. They are available for unplasticized polyvinyl chloride in windows, profiles, doors and frames and are supported by standards for a controlled loop. Those are the harmonized product standards for windows EN1 4351-1 [4] and for PVC-U recycling EN 17410 [5]. The results are window frames with considerable ratios of recycled materials. The recycling opportunities of plasticized polyvinyl chloride are completely opposite. The amount of harmful and in the meantime between initial use and end of life regulated substances is high. The grinding of the material is laborious, but a prerequisite for mechanical recycling. Consequently, recycling amounts remain small [6] in research projects (e. g. REMADYL [7]) or cable or film recycling.

Finally, recyclability of plastic construction products depends on the availability of voluntary take-back schemes and standardization. Standardization is required to determine wastes for collection, the quality of recycled plastics as well as requirements for use of recyclates in products. At the same time, take-back schemes need advertisement and logistics. Ideally, this information would be distributed with the technical documentation of a product. It is the information of recyclability regarding the end-of-life products and materials suitability and process availability. Regarding the use of recycled plastics in construction products the European standards and requirements must be considered. To a certain extent they comprise particular requirements for the use of secondary raw materials. The relevant standards and examples for recycling schemes, and requirements for the use of recyclates were summarized. The need for specific standards for recycling was accentuated in the German strategy for resource efficiency—Deutsches Ressourceneffizienzprogramm III (Measure 54) [8]. The measure is necessary for plastic waste in general, but in particular for the recycling of standardized and regulated construction products and the use of secondary raw materials.

3 Research process, methods

The study focused on four areas to determine how high-value plastic recycling can be achieved in the construction sector: the creation of a market study and a determination of construction plastics in the anthropogenic stock, the potential of take-back schemes, the status and potential of recycling techniques and the current use and future potential of recycled plastic in building products. In this chapter, we present the main research subjects of the individual areas and the methodology used to investigate them. Table 1 gives an overview of the applied methods and data.

Market study and a determination of construction plastics in the anthropogenic stock

In a first step, it was identified which individual construction products made of plastic are on the German market. To obtain an overview of the material-specific plastic diversity in buildings, the types and quantities of plastic used were identified for each product. This market analysis is the starting point for the further investigations.

The lists of harmonized specifications (hEN and EAD) derived from European Construction Products Regulation (EU) No. 305/2011, as well as the administrative regulation template for technical building regulations (especially parts B, C and D), initially served as the basis for the compilation of the comprehensive product list of plastic construction products used [9, 10] Those lists were reviewed with respect to construction products predominantly plastic- or bitumen-based. The relevant construction products were noted and included in the product list. To ensure the clarity of the compiled product list, the construction products being evaluated were classified into four levels (see chapter results and discussion). After identifying the various plastic construction products, an assessment of current market volumes (in terms of quantities produced and installed) was conducted. For the time being, data from the production statistics of the German Federal Statistical Office according to the list of goods (nine-digit data) were used as the basis for the production quantities [11]. However, a review and assessment quickly indicated that the data from the Federal Statistical Office alone is insufficient for clearly allocating the varying production volumes to the respective construction products

Table 1 Methods and data used

Issue	Methods/data sources
Market study and anthropogenic stock	Analysing statistical data, literature research, expert interviews
Take back schemes	Literature research, expert interviews, internet search
Recycling techniques	Literature research, internet search, expert interviews
Recycled plastic in building products	Analyzing norms, internet search, expert interviews

researched. Through the use of the various association and industry statistics, along with data from specialist literature and the Federal Statistical Office, it was possible to make an initial determination of the quantities currently installed in German buildings. In interviews with industry experts, manufacturers and associations, the quantities determined in this manner could be confirmed or supplemented.

To determine the dynamics of the anthropogenic stock of building products made of plastics, the quantities determined above were offset against data on the growth of plastic processing in the construction sector. These data were drawn from a biennial survey of the plastics market. The development of the input into the anthropogenic stock could, therefore, be based on the specifically-determined amount consumed in 2017, and could be calculated retroactively back to 2003. Data from the waste statistics (Technical Series 19) of the Federal Statistical Office were used for the output-side analysis of the stock list [12]. The following waste types associated with construction and demolition waste were considered relevant: Plastics from construction and demolition waste (waste code: 170203), mixed construction and demolition waste (waste code: 170904), insulation materials (waste codes: 170603 and 170604), cable waste (waste code: 170411), and plastic waste (excluding packaging) from the gardening and landscaping sector (waste code: 020104). It can be assumed that the wastes listed under codes 170203 and 020104 are exclusively plastics. The corresponding proportion of plastics for the other waste types was estimated on the basis of different statements from experts and plausible assumptions.

An estimate of future developments was made for both the input- and output-side considerations to be able to draw conclusions regarding the future development of return flows from the stock list.

For more detailed information on the assumptions and calculations compare chapter 2.1.1–2.1.3 of the study, this report is based on [13].

Investigation into the role of take-back schemes

In take-back systems, products are recovered following their use phase. Take-back schemes can take different organizational forms, such as deposit systems, loan models where products are rented out, or simple take-back. There are several take-back systems in the German construction sector. The goal of the analysis was to provide a comprehensive list of the individual systems and their characteristics. Furthermore, the basic conditions for functioning recovery systems should be identified to derive recommendations for their successful application and transfer on other products. Information was compiled from literature, expert interviews and data available online.

Recycling techniques

In Germany, mechanical recycling of plastic products is widespread. Since plastic building products are very diverse, the aim of reviewing the German recycling sector was to identify which processes are most suitable for construction products and to make recommendations for increasing recycling. This was done through research in specialist literature and expert interviews.

Determining the potential of recycled materials in building products

To outline the potential use of recyclates in plastic construction products, the general prerequisites for the use of recyclates in the manufacturing of building products were examined in detail. Due to their high relevance, pipes in particular but also cable ducts, are considered, with current standards and requirements for the use of recyclates being explained and the technical limits and further obstacles outlined. Based on this, an assessment was made of the potential use of recyclates in the four major application areas of pipes, profiles, insulation materials, and others.

Results and discussion

Plastic building products and anthropogenic stock

In Germany, the total quantity of installed construction products made of plastic was 2.64 million t in 2017. The shares of the aggregated application areas are shown in Fig. 1.

In the pipes sub-segment, the data situation was mostly satisfactory. In addition to the data from the production statistics, the statistics of the Trade Association of the Plastic Pipe Industry were used as a supplement to determine current market volumes. A review and evaluation of the data indicated an annual production volume of around

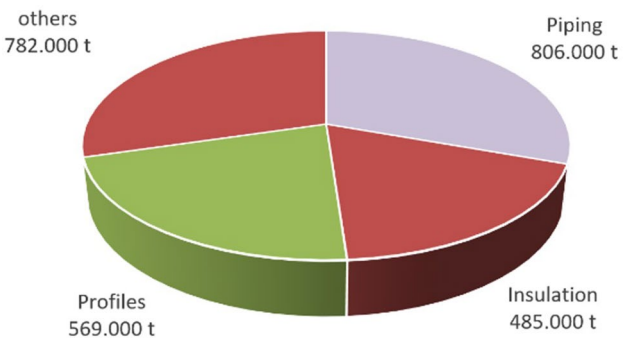

Fig. 1 Calculated installed quantities for the four aggregated application areas in 2017 in tonnes

1.03 million t of plastic piping, with pipes made of polyethylene and polyvinyl chloride accounting for the largest share in terms of overall mass. The installed mass was estimated to be around 0.81 million t per year (see Fig. 1) of which around 0.30 million t comprised PE, 0.19 million t PVC, 0.08 million t PP, 0.05 million t GFRP, and 0.19 million t of plastics that could not be precisely identified [11, 14, 15].

For the profiles sub-segment, the production in 2017 was around 0.91 million tons. Profiles are continuously extruded semi-finished products that are then used to manufacture final products such as the frames of windows or doors. The material most often used here was PVC. Due to a very high export surplus within this sub-segment, the mass was estimated to be around 0.57 million t (see Fig. 1) of which around 0.41 million t comprised PVC, 0.02 million t GRP, 0.11 million t PE, and 0.03 million t of plastics that could not be precisely defined [11, 14].

In the insulation sub-segment, data from technical literature and associations (e.g., from interviews with experts) were mostly used [16, 17]. It should be noted here that the obtained information mostly refers to the three insulation material types of expanded polystyrene (EPS), extruded polystyrene (XPS), and polyisocyanurate, respectively, polyurethane. No information was available on the market quantities of other insulation materials (e.g., those made of phenolic resin rigid or polyethylene foams), although it was confirmed during the expert interviews that these make up a negligible proportion in terms of the total quantity of insulation materials installed.

For the last sub-segment, others, the production mass of waterproofing materials, floor coverings, and cables are especially relevant. Due to their versatility and the large number of different products in the sub-segment, the availability of data on the current market quantities of the different construction products turned out to be highly heterogeneous. Therefore, to estimate the quantities of waterproofing membranes, floor coverings, and cables, data from the technical literature or corresponding association statistics was utilized. For data on other products belonging to the others sub-segment, production statistics were employed [11, 14]. The installed volume for the sub-segment others was estimated to be approximately 0.782 million t, of which bitumen-based roofing, plastic roofing and waterproofing membranes accounted for around 49% [18, 19]. The remaining production mass could mainly be attributed to floor coverings (around 23%) and cable materials (9%) [20].

After aggregation of the sub-segments of pipes, profiles, insulation, and others, the shares by plastic type corresponds to the installed volumes (2.64 million t) in 2017, as shown in Fig. 2. Around 30% of the installed volume could be attributed to PVC plastic, and around 16% to PE. Other plastics of particular relevance in terms of volume include EPS (8%), PIR/PUR (5%), PP (4%), and GFRP (3%).

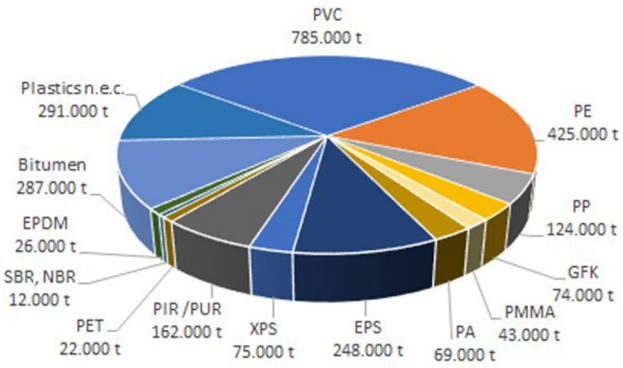

Fig. 2 Determined installed quantities by type of plastic in 2017 in tons

Based on the methodology described above, the past and future development of the anthropogenic stockpile of building materials made of plastic have been estimated. The total waste volume for the period between 2005 and 2017 was around 7.94 million t (see Fig. 3). At 6.4 million t, the plastics contained in mixed construction and demolition waste (waste code: 170904) make the largest share of waste mass. Additionally, around 0.4 million t of plastic cable waste (waste code: 170411) and around 0.2 million t of insulation materials (waste codes: 170603 and 170604) accrued in that period of time. Both, plastic from cable waste and plastic from insulation materials were collected together with other cable and insulation material. Only 1.16 million t of plastics (14.6%) were collected separately (waste codes: 170203—plastic waste collected separately from construction and demolition waste and 020104—agriculture, horticulture, pondmanagement, forestry, hunting, and fishing).

The net input (input minus output) of the anthropogenic stockpile in the period between 2005 and 2017 can thus be estimated to have been roughly 22.4 million t. This corresponds to an average annual increase of 1.7 million t (see Fig. 4). The projection by 2030 indicates that the anthropogenic stock will roughly double by 2030 compared to 2005. The application of plastics in the construction sector definitely increases. These extrapolations are based on the available data and should be treated as a rough estimate. Nevertheless, the amount of plastics applied in the construction sector will definitely increase and thus the anthropogenic stockpile too.

The large difference between the volumes of plastics consumed and those generated as waste in the construction sector is primarily a function of the industry-specific service live times of the various product types and the increased use of the material in the construction sector in recent decades. Compared to plastic products from other sectors, such as packaging (typical service lives of a few days or weeks), plastic-based construction products are

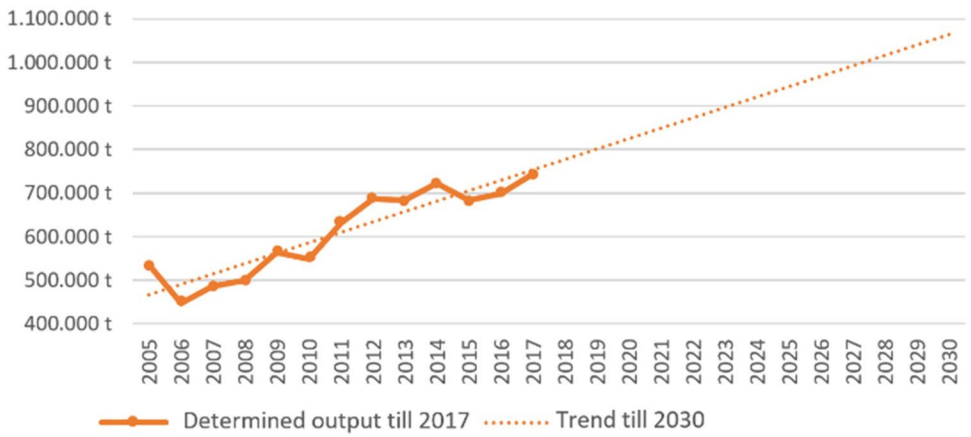

Fig. 3 Determined waste mass of discarded plastic construction products (output) for the period from 2005 to 2017

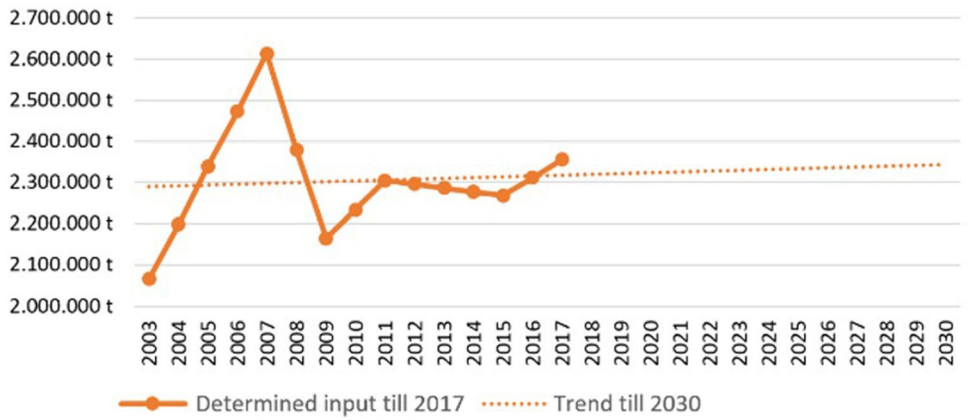

Fig. 4 Annual mass of installed plastic construction products (input) for the period 2003–2017

characterized by significantly longer service lives and, in some cases, remain in the building stock for several decades. A large part of the waste currently generated during dismantling was installed many decades ago. Plastic products currently being used will, in turn, not emerge in the waste stream for several decades. This state of affairs represents a major obstacle to holding manufacturers responsible under the 'polluter pays' principle, or implementing manufacturer-supported take-back and recycling systems for currently returning streams. The utility of the mechanical recycling of current and, from today's point of view, partially contaminated post-consumer waste, must also be examined on a case-by-case basis and, depending on the ingredients that were initially used. On the other hand, longevity as such already offers ecological advantages over the use of plastics in products with short service lives.

The role of take-back schemes

Take back systems offer the following solutions to improve high-quality recycling:

1. The material is separated during dismantling and thus kept isolated resulting in a higher purity waste fraction. Higher purity waste streams, in general, translate to better recyclate quality as can be seen from PET-bottle collection in the post-consumer sector [21].
2. In a high-quality recycling take-back scheme, the material taken back is used in the manufacturing of new products. This is an incentive for the manufacturing companies to implement design-for-recycling principles in their production process. Here, in contrast to the standard recycling path, the product manufacturer sees a (financial) return of the effort put into applying design-for-recycling. This is the case for PVC-U profiles with long fiber reinforcement that include special markers for reliable identification [22].

On the other side, the implementation of take-back schemes has some challenges that need to be considered

1. Reverse take-back logistics are needed to collect the waste. This includes separate collection sites at the construction or dismantling site, provision of containers,

and transport to intermediate collection sites or directly to treatment facilities
2. Waste volumes need to be high enough to justify the expenses for separation, transport and recycling.

The following criteria that recycling of plastic construction materials have to face in general apply to take-back schemes as well

3. Separation of the waste has to be feasible. While windows, doors or carpets can be removed and separated quite easily in the demolition process. This is challenging and, according to experts, most of the time financially not viable for products like underground pipes or isolation panels fixed by glueing.
4. The recycled material produced has to be financially competitive compared to virgin material

Different take-back schemes have been analysed. Most of them are focused on the sectors of PVC, floor coverings and agricultural films, compare Table 2. For insulation materials, no larger scale take-back system exists. PVC-U take-back systems function well for window and door profiles. Here, considerable amounts are taken back and recycled in a controlled loop. For pipes, a suitable recycling process exists as well but here the difficulties of separation during dismantling together with long product life time result in lower relative amounts that are recycled. While PVC-U take-back systems are organized industry wide, take-back systems for textile floor coverings are implemented by just a few companies. Those carpets are reused or downcycled to carpet backings. Additionally, in particular agricultural films, are collected and partly recycled to films again in considerable amounts.

In general, it can be stated that the implementation of take-back systems is a good prerequisite for high-quality recycling and should be supported if the circumstances are suitable.

Recycling techniques

Literature research and expert interviews showed that the recycling of thermoplastic plastic building products typically proceeds as follows:

- Selective dismantling and collection at the demolition or building site
- Transport to a processing plant where recyclable materials are separated from glass, wood, mineral fractions and other waste
- Regranulation and recompounding

Besides mechanical recycling, other techniques of high-value recycling are solvent-based processes and chemical recycling. In general, mechanical recycling is the most sustainable method. Solvent-based processes can be a suitable solution in cases where recycling-incompatible substances, for example additives, need to be removed from the waste stream. An example for a solvent-based process is the creasolve process which was in pilot stage during the study but went bankrupt in march 2022. The process carried out consists of dissolution, cleaning, precipitation and extrusion. The solvent is purified by distillation and

Table 2 Take-back schemes for plastic building products in Germany

Take back scheme	Products and materials	Recyclate use
Rewindow	Profiles, PVC-U	Recycled back to profiles
Roof collect	Waterproofing membranes PVC-P and blends	Downcycling to protective matting
Plastic pipe association	Pipes PE, PP, PVC	Recycled back to pipes
The austrian working group for plastic pipe recycling (OAKR)	Pipes PE, PP, PVC	Partly recycled back to pipes
Working group on the recycling of PVC floor covering (AGPR)	Flooring PVC-P	Recycled back to floor coverings
Restart	Flooring Vinyl, linoleum, PA6	Large parts recycled back to flooring
Interface	Flooring PA, PVC, natural rubber PVB, PVC-P	Reuse of product if possible
Greenstream	Carpet tiles	Reuse
Anglo recycling	Carpet edge trim and offcuts PP, Wool, PVC-P	Downcycling to carpet backing

then regenerated and reused [23, 24]. The additives to be removed depend on the feedstock, for building products the flame retardant HBCD plays a major role. Chemical recycling is still in development but experts agree that it should only be used for waste streams that cannot be mechanically recycled and would otherwise be discarded as substitute fuel. It remains to be seen whether it can serve this purpose from a sustainability perspective.

The choice of recycling techniques depends strongly on several factors, the important ones being

- Can the material be mechanically recycled
- What quality is the waste stream and are there incompatible additives in the products
- What are the possible achievable prices for the recyclate

In general, it can be stated that PVC-U, e. g. from windows and doors as well as most forms of pipes and agricultural films are recyclable by means of available recycling structures and techniques. Floor coverings have the potential to be recycled to high-quality products if they are designed for recycling, e. g. by a wear layer made of a single material. Recycling of PIR /PUR insulation products is challenging as well. Here the low mass of the product, the difficulties of separation during dismantling and the non-thermoplastic nature of the material are to be considered. Significant difficulties arise for GFRP since neither the fibers nor the resin are recyclable so far.

The recycling of plastic building products can only achieve its full potential when it is taken into account throughout the whole product life cycle and by all involved stakeholders. It includes, for example, using design-for-recycling principles during product design and using appropriate techniques in the building process which allow for disassembly and separation at the time of dismantling. Especially glued, or subterranean installed products are hard or impossible to recover in a financially viable manner.

The long product life time makes these considerations on one hand especially important, because products being used now will reach their end of life stage at a point of time where a circular economy is expected to be state of the art. On the other hand, long product lifetimes pose a significant challenge because regulations and recycling techniques might change considerably up until the time when the product enters the recycling phase.

In general, it can be stated that for many products the possibility of recycling exists but this goal must be pursued by all stakeholders of the value chain and will most likely result in significantly higher costs for these stakeholders.

For more detailed information on the process of obtaining the primary information by literature review an interviews, see chapter 4 of the study this report is based on [13].

The potential of recycled materials in building products

The recyclability of plastics is influenced by different properties. As plastic waste, especially in the post-consumer sector, accumulates as a heterogeneous mixture and the different types of plastic are often very difficult to mix with one another, separation into individual plastic fractions (for example, by means of near-infrared spectroscopy) is usually a mandatory prerequisite for the production of a high-quality recyclate. The enormous variety of plastic types, blends, colorants, and additives used often make this step significantly more difficult. Prerequisites for the use of plastic recyclates are summarized in the following bullet points:

- Well-sorted batches
- As few contaminants and impurities as possible
- As little degradation of the polymer chains as possible
- Fulfillment of structural engineering standards and customer requirements
- Good processability
- Modified process/plant technology

Use of recycled materials in pipes

Plastic piping systems are subject to numerous different quality requirements depending, for example, on the material used (i.e., PVC-U, PP or PE) or the type of application (e.g., wastewater, drinking water, or gas supply) of the pipe. The manufacturers of plastic pipes therefore typically have their products voluntarily certified by an authorized body, thus providing the quality requirements stipulated by the relevant standards.

In the case of profiled pipes for underground, non-pressurized sewers and pipelines, PVC-U return material and recyclate derived from PVC-U pipes and fittings may be used. Return material and recyclates from PVC-U products other than pipes and fittings may be used in either a middle layer of specific pipe types, or added to virgin material, recycled material, or a mixture of the two. With respect to profiled pipes for underground, non-pressurized sewers and pipes made of PP and PE, the use of returned and/or recycled material from products other than PP pipes or fittings, or corresponding to PE pipes or fittings, is excluded (in contrast to PVC-U) (DIN EN 1401, DIN EN 13476) [25, 26]. The reason for the different requirements is that in the production of PVC-U pipes, subsequent stabilization is relatively easy to carry out, in contrast to the production of PE/PP pipes.

For the production of drinking water pipes, the current standards do not currently permit the use of any recycled material or recyclates (DIN EN ISO 15874, DIN EN ISO 15876, DIN EN ISO 15877, DIN EN ISO 22391) [27–30]. According to experts, this is due to the problematic technical issues that arise from the fact that drinking water pipes are subject to pressure. Mechanical properties (e.g., MFR or impact strength), like geometric and color properties, are far easier to influence and therefore do not constitute directly limiting factors.

In Germany, old pipes have been collected and recycled since 1994 by the manufacturers represented by the German Plastic Pipe Industry Association (KRV). The recyclates obtained subsequently are primarily used in wastewater, cable protection, and drainage pipes. According to the trade association, the amount of scrap currently recycled in the pipes sector is estimated to be around 40,000 tons (in 2018). The KRV's goal for the coming years is to double this amount (target: 82,000 t of recycled scrap) (KRV Impulse 2019). A higher amount of secondary plastics used in the area of piping systems is not considered feasible currently due to various factors that limit the use of recyclates. According to the KRV, these include:

- The fluctuating/insufficient quality of recyclates
- Their inconsistent availability
- Price differences between laboriously- and expensively-produced recyclates and inexpensive virgin materials
- Insufficient mechanical properties (especially mechanical strength)
- Customer requirements concerning the color of the products to be manufactured
- Negative odor properties in manufactured products
- Disadvantages in production (e.g., higher machine wear, lower production speed)
- Continually increasing quality requirements from customers and regulators

Use of recycled material for the production of window profiles

In window profile production, recyclates make up 18% of the feedstocks currently used, and a well-functioning material cycle (Rewindo) has already been established. However, experts estimate the potential for using recyclates to be much higher, at 50–70%. There are a number of reasons why the current use of recyclates remains low. On one hand, there are economic factors. The development and application of technologies is still highly complex and cost-intensive. The high prices for recyclates also reduce their more widespread use in window profile production. On the other hand, current standards also limit the use of recycled materials. In principle, window profiles must meet stringent requirements in terms of weathering and UV stability. Recyclates may be used in profile cores, but the corresponding standard does not permit this in outer walls. The trend towards composite systems also reduces the good recyclability of old windows. With the installation of glass fibers or aluminum parts in the profile core, separation, if viable at all, is only possible with increased effort and additional costs. As with pipes, the demand for recyclates for window profile manufacturing cannot be met by the existing supply either. [31–34]

Insulation materials

*C*ompared to pipes and window profiles, the current situation for insulation materials with respect to the use of recyclates is generally worse. Appropriate take-back systems have not yet been established, as the quantities of recycled material remain too small. However, as these are very likely to increase in the future, a take-back system is already under development. Furthermore, insulation boards with recycled content cannot yet be produced to the usual facade standard. Mechanical recycling is not optimal for PIR/PUR insulation materials, which is why raw material processes appear more promising. [35, 36]

Others

The examples for the uses of plastic recyclates in the field of other building products are fairly diverse. Based on research presented in the catalogs of dealers and manufacturers, the following products can be noted by way of example: Cable ducts, sanitary supplies (e.g., odor traps), panels (e.g., drainage or construction panels), fence elements, amphibious protection elements, pallets, construction films, spacers, noise protection elements/walls, roadway protection elements, beacon bases, delineator bases, guide cones, containers and tanks, raised beds, palisades, grass stop plates, grass pavers, garbage cans, mats (e.g., maintenance path mats on flat roofs or fall protection mats), railroad crossings, public furniture.

Recommendations

Based on our research, the following recommendations can serve to improve plastics recycling in the construction sector. An in depth discussion can be found in chapter 7 of the report this paper is based on [13].

Improvement of transparency: technical documentation and product labeling

A product's recyclate content as well as its recyclability are valuable information and should be included in technical documentations and product labeling on a mandatory

basis. This information can function as a valuable guide for informed user decisions. At the same time, the cost and effort for their declaration is minimal. Where possible, the information may be passed along with the product based on digital markings such as a QR code or a watermark.

Cross-sector recycling

If, for reasons of low quantity availability, waste from the construction sector cannot be reused for the manufacturing of the same product (e.g. pipe-to-pipe), efforts should be made to utilize these materials for other construction products. Especially in the case of products that do not require proof of usability in accordance with Part D of the Model Administrative Rules on Technical Building Regulations [9] and for which there are no recognized rules of technology, there is still great potential for increasing the use of recycled materials.

Recyclate use in packaging

High recyclate contents in packaging for building products should be promoted. The feasibility has been demonstrated in various products such as stretch and shrink film, big bags, pallets, canisters bottles and others [37–40]. One way of promoting recyclate use could be a mandatory recyclate quota for films as proposed by various stakeholders. Another approach would be to strictly enforce existing regulations for separation of plastic waste at the building sites to cycle the packaging materials.

Application of design for recycling

As stated before, high-quality recycling does not start at the waste stage of a product but needs to be considered in the production process as well. This means applying design-for-recycling principles and thus avoiding materials, material combinations and additives not suited for recycling. In the case of toxicologically critical additives this implies a conservative, anticipatory approach that takes into account the long product life times and changes of regulation in that time. Product design needs to consider dismantling and separation from the waste stream and to minimize packaging.

While regulatory approaches to enforce design-of-recycling are difficult to implement, all measures promoting or enforcing recyclate use will promote design-for-recycling principles in the long run as a trickle down effect.

Establishment of take-back schemes

Take-back schemes have been shown to provide very good opportunities for high-value recycling when they create well-defined closed loops. The establishment of take-back schemes should thus receive more scrutiny from the industry side. Research can here elucidate further suitable material streams and organizational parameters that can help to amplify the number of take-back schemes and to make them more efficient and profitable.

Life span

Even an efficient recycling process has a considerable ecological footprint. For products whose lifetime is governed by their durability, measures like extending product lifespan or improving repairability is therefore preferred to recycling from a sustainability point of view. In general, the use of plastic for building products is ecologically preferable compared to single use or short live plastic products. Nevertheless, especially against the background of the long lifetimes of building products, the long-term goals of the circular economy and also CO_2 neutrality in the middle of the century must definitely be kept in mind in the further development of building products made of plastic.

Conclusion

Plastic use in the building sector is increasing and is expected to continue increasing resulting in an accumulation of plastics in the anthropogenic stock. The main polymer types used are PVC, PE and EPS, while the main product types are piping, profiles and insulation. The long product life times in the building sector increase the difficulty of recycling these materials and products because of legacy additives and incompatibility with extended producer responsibility. However, a pure waste stream is the prerequisite for high-quality recycling. Provision of information and data on a material's attribute e.g. via labelling is therefore vital for high-value recycling streams. Easy dismantling and design-for-recycling need to be implemented to improve recycling in the future. Additionally, take-back schemes are a good way to achieve pure waste streams but cannot be implemented for all waste fractions. The use of recyclate in plastic building products is subject to the precondition that high-quality recyclates are available and that the regulatory framework for its use is in place.

Acknowledgements The study is based on a research project commissioned by the Federal Environment Agency of Germany. A 2-year study was carried out on the topic of "Promoting high-quality recycling of plastics from demolition waste and strengthening the use of recycled materials in building products in line with the European Plastics Strategy" FKZ 3719 34 314 0. The authors would like to thank János Sebestyén, Michael Ritthoff, Laura Perschel, Jonathan Kirchhoff and Robin Kocina for their contribution to this report.

Funding Open Access funding enabled and organized by Projekt DEAL.

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