Dr. Gerald Altnau – Managing Director CreaCycle GmbH, Germany
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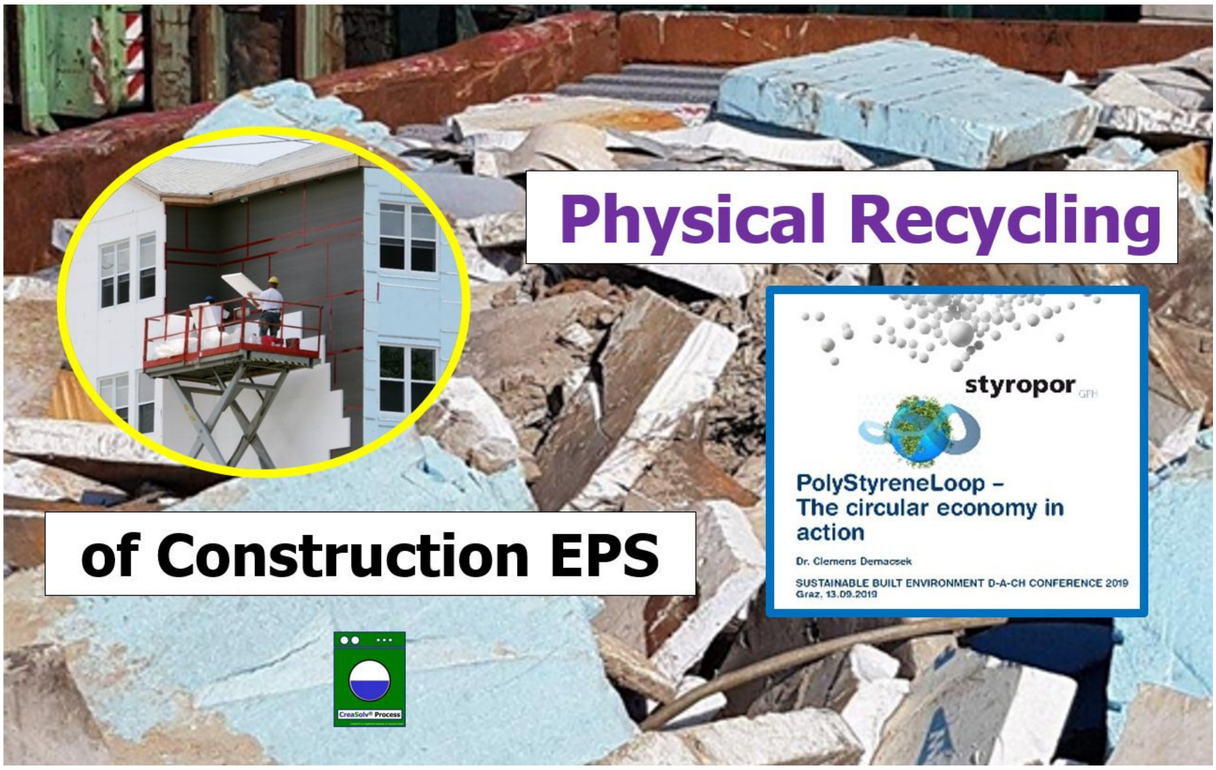
PolyStyreneLoop – The circular economy in action

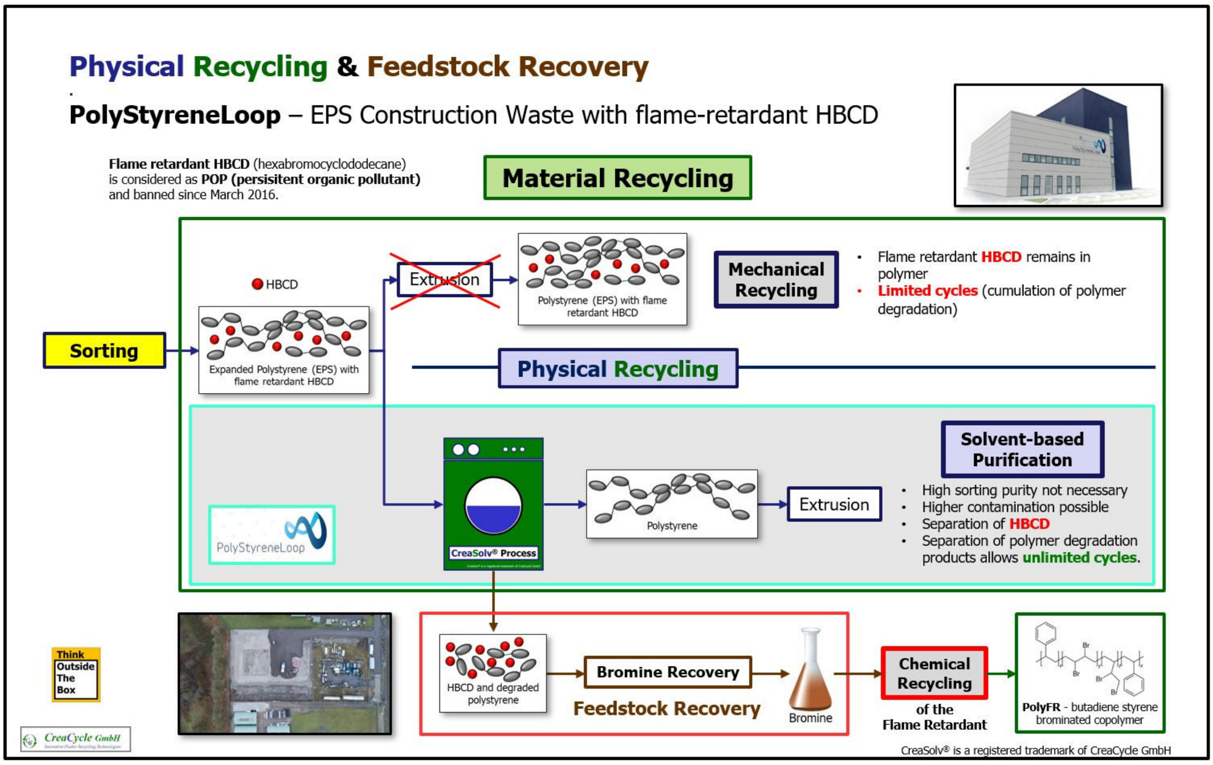


On September 13, 2019 Clemens Demascek, Managing Director of "Güteschutzgemeinschaft Polystyrol-Hartschaum" presented the PolyStyreneLoop project at the **Sustainable Built Environment Conference 2019** in Graz Austria.

For decades polystyrene (PS) foam is known as an efficient insulation material in the building and construction environment. At the end of its very long useful life, the waste remains a valuable material source for a variety of products. However, the flame retardant HBCD, which has been used since the 1960s until 2017, is considered a pollutant and millions of tons of PS foam waste can no longer be regularly recycled.

PolyStyreneLoop is developing a solution with a physical-chemical recycling process, based on the CreaSolv® Technology (solvent-based purification). The applied technology turns PS foam waste into new high-quality raw material. During the recycling process, impurities, such as cement or other construction residues, as well as the imbedded flame retardant HBCD are safely removed. The HBCD is destroyed, while the valuable bromine component and polystyrene are recovered.

When mechanical recycling needs a high sorting purity of waste streams and fails on imbedded additives and impurities (including hazardous and toxic ones) or multilayer packaging, the CreaSolv® Process based on a Solvent-based Purification works like a washing machine on a molecular level.



In 2020 an industrial scale demonstration plant (with the capability to handle 3.3 kt of PS insulation foam waste per year) will be built in the Netherlands. The plant is aimed at starting up by the beginning of 2021. Subsequently the technical, economic and environmental viability of this new recycling process will be assessed. When proven to be successful, the process will be further rolled out with additional commercial plants in other countries throughout Europe.

In order to protect resources and our environment, high-quality recycling technologies for plastic waste are required, which allow the reuse of polymers without breaking up the polymer chains.
CreaCycle GmbH and the Fraunhofer Institute for Process Engineering and Packaging (IVV) in Freising, Germany combined their competencies in a cooperation aimed at "Plastic/Raw-Material Recycling with a Solvent-based Purification Technology" (selective extraction) and developed the CreaSolv® Process that is based on physical changes and leaves the polymer composition intact.
Proprietary CreaSolv® Formulations from CreaCycle with the lowest risk potential possible for user and environment dissolve selectively a target polymer. This reduces besides the hazard also the cost for the equipment. After the separation of imbedded impurities or undesired polymers the recycled polymer can be reused in its original application.

CreaCycle GmbH
Auf der Artwick 74
41515 Grevenbroich
Germany
Email: gerald.altnau@creacycle.de
Homepage: www.creacycle.de

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PolyStyreneLoop – The circular economy in action

Demacsek C[1], Tange L[2], Reichenecker A[2], Altnau G[3]

[1]Güteschutzgemeinschaft Polystyrol-Hartschaum, Brückenstraße 3, 2522 Oberwalters-dorf, Austria
[2]PolyStyreneLoop Cooperative, Frankrijkweg 10, 4538 BJ Terneuzen, Netherlands
[3]CreaCycle GmbH, Auf der Artwick 74, 41515 Grevenbroich, Germany

info@polystyreneloop.eu

Abstract. For decades polystyrene (PS) foam is known as an efficient insulation material in the building and construction environment. At the end of its very long useful life, the waste remains a valuable material source for a variety of products. However, the flame retardant HBCD, which has been used since the 1960s until 2017, is considered a pollutant and millions of tons of PS foam waste can no longer be regularly recycled.
PolyStyreneLoop is developing a solution with a physico-chemical recycling process, based on the CreaSolv® Technology. The applied technology turns PS foam waste into new high-quality raw material. During the recycling process, impurities, such as cement or other construction residues, as well as the imbedded flame retardant HBCD are safely removed. The HBCD is destroyed, while the valuable bromine component and polystyrene are recovered.
In 2019 an industrial scale demonstration plant (with the capability to handle 3.3 kt of PS insulation foam waste per year) will be built in the Netherlands. The plant is aimed at starting up by the end of 2019. Subsequently the technical, economic and environmental viability of this new recycling process will be assessed. When proven to be successful, the process will be further rolled out with additional commercial plants in other countries throughout Europe.

1. Introduction

Polystyrene (PS) foam is one of the most widely used insulation materials ensuring climate control and energy efficiency of buildings. Over the lifetime, the energy savings achieved during heating save a multiple of the fossil resources required for its production. However, in the sense of a modern, low-carbon, resource and energy-efficient economy every effort must be made to use all resources sparingly. That's exactly where PolyStyreneLoop starts. It is a new recycling process for polystyrene (PS) foam that can be used for both expanded polystyrene (EPS) and extruded polystyrene (XPS). For this purpose, a demonstration plant will be built in the Netherlands. The primary aim is to recycle insulation materials that contain the imbedded flame retardant HBCD (which is no longer used). As PolyStyreneLoop will start with the recycling of EPS, the focus will be placed on this material in the remainder of this article.

EPS is a lightweight, rigid, plastic foam insulation material consisting of 98 % air and 2 % polystyrene. It is typically used in External Thermal Insulation Composite Systems (ETICS) and for flat roof, perimeter or impact sound insulation. Builders often choose EPS, because it is cost-effective, durable and easy to install.

1.1. Global and European Regulations for HBCD

To meet national fire regulations Hexabromocyclododecane (HBCD) has been used in many European countries since the 1960s until 2017 as a flame retardant in insulation materials made of expanded polystyrene (EPS) and extruded polystyrene (XPS). In 2013 HBCD was brought under the Stockholm Convention regime due to its persistent, bioaccumulative and toxic properties as well as its potential for long-range transport and has been listed as a Persistent Organic Pollutant (POP) [1].

In Europe the provisions of the Stockholm Convention were implemented in Regulation (EC) No 850/2004 [2]. The concentration limits for HBCD in articles and waste were set in amendments to this regulation. HBCD in articles is allowed in concentrations equal to or below 100 mg/kg [3]. HBCD in waste is allowed in concentrations below 1,000 mg/kg [4].

The REACH regulation listed HBCD already in 2011 as a persistent, bioaccumulative and toxic substance [5] and prohibited it to be placed on the market or used after 21 August 2015. After this date HBCD could still be used for EPS until 21 August 2017 by companies granted with an authorisation under REACH. Since 1 January 2015, producers in e.g. Austria, Germany and Switzerland have converted to the new polymeric flame retardant pFR.

Table 1. Allowed HBCD concentrations.

HBCD concentration	Concentration limit for HBCD in products and waste	Legislation
≤ 100 ppm	Products placed on the market (unintentional trace contamination)	EC 2016/293
< 1,000 ppm	Recovery or disposal	EC 2016/460
≥ 1,000 ppm	Physico-chemical treatment (i.e. PolyStyreneLoop) or incineration	Basel Convention

1.2. Disposal of Construction EPS Waste today

One option of disposal is mechanical recycling, where EPS waste is ground into granulate. It might be added to thermal insulation panels for instance, but also serves as an aggregate for lightweight concrete, bound EPS ballastings [6] and insulating plaster, and acts as a pore inducer in the brick industry. This recycling process is possible for packaging EPS without HBCD and construction EPS with pFR, but not for old construction EPS with HBCD, as the concentration limit of 100 ppm for HBCD in the recycled product would be exceeded.

Another option is to use the calorific value of EPS in incineration plants and cement factories: 1 kg of waste saves 1.3 litres of valuable heating oil. The advantage of this process is that the requirements regarding cleanliness of the EPS waste are low. In a large-scale test in the Würzburg waste incineration plant [7] in 2013 it was proven that burning PS foam containing HBCD has no negative effects on the environment. The flame retardant HBCD is totally destroyed [8]. Even a proportion up to 30 percent by volume (or 2 wt%) of PS foam containing HBCD at the waste incineration changes nothing in terms of the composition of the end products such as slag, dust and filtration residues, owing to the high temperature applied. This means that old construction EPS waste containing HBCD can be burned in any state of the art municipal incineration plant [9].

In many European countries landfilling is not an option, because there are restrictions for waste with a high content of organic carbon (TOC). In this respect, EPS waste is no different from other insulation material waste of organic origin such as cork, wood fibre or hemp.

In 2017 the total EPS foam waste stream in Europe amounts to 527,000 tons. Of this, 98,600 tons come from the demolition of buildings [10]. This construction EPS waste stream will increase in the next decades and secures enough input for the future physico-chemical recycling.

1.3. EU Plastics Strategy

In December 2015, the Commission adopted an EU Action Plan for a “Circular Economy”. There, it identified plastics as a key priority and committed itself to ‘prepare a strategy addressing the challenges posed by plastics throughout the value chain and taking into account their entire life-cycle'. In 2017, the Commission confirmed it would focus on plastics production and use, and work towards the goal of ensuring that all plastic packaging is recyclable by 2030 [11].

1.4. EUMEPS EU Voluntary Pledge

The association "European Manufacturers of EPS" (EUMEPS) has submitted a voluntary pledge [12] on behalf of its members, as requested in Annex III of the EU Plastics Strategy, to indicate their recycling targets by 2025. Many companies in the value chain are already working to ensure that the EUMEPS pledge can be realised.

Table 2. Recycling targets of the EUMEPS EU Voluntary Pledge.

Object	Polymer	Baseline	Pledge	Quantities 2025 (estimates)		Quality	New Technologies involved
				Market	Recycle		
Insulated Packaging (e.g. fish boxes)	EPS	Conversio Study 2017	50 %	140,000	70,000	High quality EPS	Food grade quality potential (EPS SURE)
Protective Packaging (e.g. appliances)	EPS	Conversio Study 2017	50 %	230,000	115,000	Standard EPS	
Building Deconstruction	FR-EPS EPS	Estimated 2025 market	27 %	150,000	40,000	High quality EPS	PolyStreneLoop – HBCD removal and recycling of bromine. Chemical recycling.
New build and renovation	FR-EPS EPS	Conversio Study 2017	80 %	40,000	32,000	Standard EPS	
Civil Engineering New build and Deconstruction	EPS		90 %				
TOTAL			**46 %**	**560,000**	**257,000**		

FR = Flame Retarded

2. PolyStyreneLoop – Physico-chemical Recycling

A demonstration plant in Terneuzen, Netherlands, shall demonstrate the technical, economic and environmental feasibility of a physico-chemical recycling process. It is seen as an opportunity to roll out a system where PS foams containing HBCD can be handled as part of the circular economy.

2.1. Cooperative and its Members

PolyStyreneLoop is a cooperative, currently counting 66 members from 14 European countries from the whole polystyrene value chain. The cooperative was inaugurated on 6th of November 2017. Members and supporters include flame retardant producers, styrene and polystyrene producers, EPS and XPS producers, EPS converters, waste collectors, industry associations, recyclers and machinery manufacturers.

2.2. Financing – Funding Cooperative, LIFE Grant and Bank Loan

The total investment of the project is € 10.4 million. Of this, € 2.4 million were provided by membership fees and supporter contributions. Furthermore, PolyStyreneLoop received an EU initiated LIFE Subsidy program of € 2.7 million. The project is known under LIFE-PSLOOP (LIFE 16 ENV/NL/000271) and runs from 2017 till 2021 with the option of an extension, if requested by PolyStyreneLoop. For XPS recycling a regional additional funding of € 1 million has been received from the Province of Zeeland in the Netherlands. The remaining financing needs are covered by a bank loan.

2.3. CreaSolv® Technology and Bromine Recovery Unit (BRU)
The CreaSolv® Technology is a development of Fraunhofer Institute for Process Engineering and Packaging IVV in corporation with CreaCycle GmbH (CreaSolv® is a registered trademark of CreaCycle GmbH). Plastic wastes are selectively dissolved with a specific proprietary solvent formulation. The components of the CreaSolv® Formulation are fully REACH registered and not considered as hazardous according to the Globally Harmonized System (GHS). This dissolution is a physico-chemical separation process. It is a pre-treatment technology, which has the potential to recover plastic molecules and separate them from legislated additives (like HBCD) or other impurities.

The process consists of three steps [13]. Steps 1 and 2 are pre-treatment for step 3.

1. PS foam waste is dissolved in tanks containing a PS-specific liquid. The solid impurities (dirt, cement and the like) are separated through filtration and then incinerated.
2. Another liquid is added, which transforms the PS into a gel, while the additive (HBCD) stays in the remaining liquid. The PS gel is then separated from the process liquids. Once cleaned, this gel is transferred into granulated polymer and the liquid, together with the additive, is distilled and re-used in a closed loop; the additives remain as sludge.
3. Finally the HBCD additive within the sludge is destructed in a high temperature waste incineration. During the last step the elemental bromine is recovered and can be reused to produce new products (e.g. modern flame retardants), thereby closing the loop.

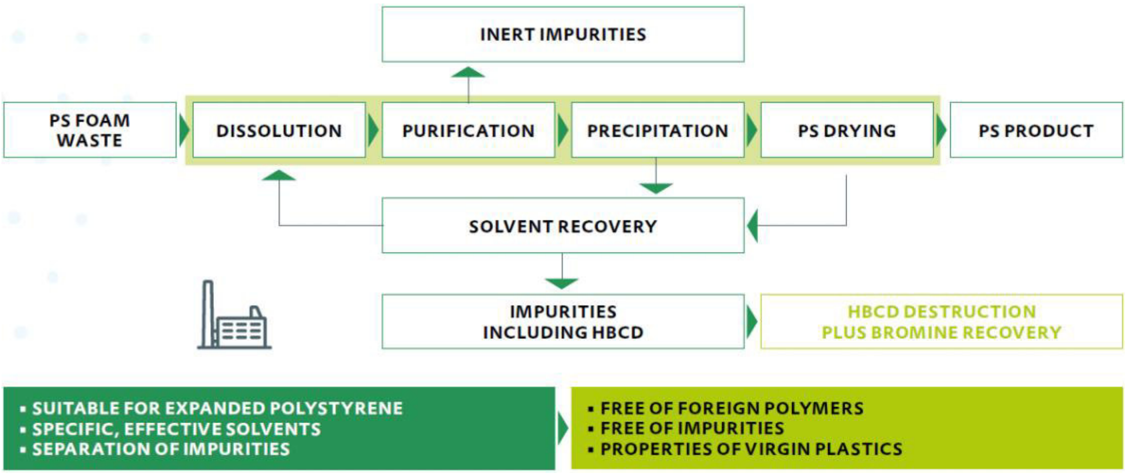

Figure 1. PolyStyreneLoop – CreaSolv® Technology and bromine recovery unit (BRU).

2.4. Technical Feasibility
The CreaSolv® Technology has been tested on laboratory scale and with PolyStyreneLoop it will be applied on demonstration scale for PS foams containing HBCD. The findings so far are that the characteristics of the recycled PS coming from PolyStyreneLoop are similar to virgin general purpose polystyrene (GPPS). The main difference is that PolyStyreneLoop GPPS recyclate is often dark, while virgin GPPS is clear. The dark colour of the recyclate comes from the carbon (graphite) that is present in part of the input material coming from new generation EPS insulation boards. As the PolyStyreneLoop project aims at closing the loop for EPS in the construction industry and the remaining graphite improves the insulating properties, less needs to be added to the raw material.

In order to utilise a CreaSolv® Plant, it is required that such a new technology be incorporated in the Basel Convention Technical Guidelines as an end-of-life (EOL) option alongside incineration. In May 2016 PolyStyreneLoop presented the CreaSolv® Technology at the Headquarters of the United Nations Environmental Programme (UNEP) in Nairobi, Kenya and got support from most global parties including many NGOs. At the 13th Meeting of the Basel Convention in Geneva in May 2017 it was finally agreed to include the individual process steps of the CreaSolv® Technology for the separation of polystyrene and HBCD as Best Available Technique (BAT) to treat PS foam waste with HBCD concentrations ≥ 1,000 ppm [14]. The guidelines are to be finalised and approved in May 2019.

2.5. Economic Feasibility

In the standard scenario, no costs for EPS waste have been set for the period 2020-2026. This stands in contrast to regulations in some countries, where it is already required to pay for the disposal of EPS waste (potential revenue upside). The forecasted sales prices have been set between the 2016-2018 sales prices of GPPS and styrene monomer. An input material conversion factor of 1.112 was taken into account. The cooperative expects that debt capital will be fully repaid in 2025.

In the worst case scenario, unlike the standard scenario, costs for the input materials occur. Although this is highly unlikely, the payback time for debt capital remains more or less unchanged.

2.6. Environmental Feasibility

TÜV Rheinland in cooperation with BASF performed a Life Cycle Assessment (LCA) [15] for the end of life treatment of EPS coming from deconstruction of External Thermal Insulation Composite Systems (ETICS). Two different end of life options for 1 ton of EPS were quantified and compared: incineration with energy recovery and the PolyStyreneLoop process. The data show that recovered polystyrene from the PolyStyreneLoop process has a 47 % lower global warming potential (GWP).

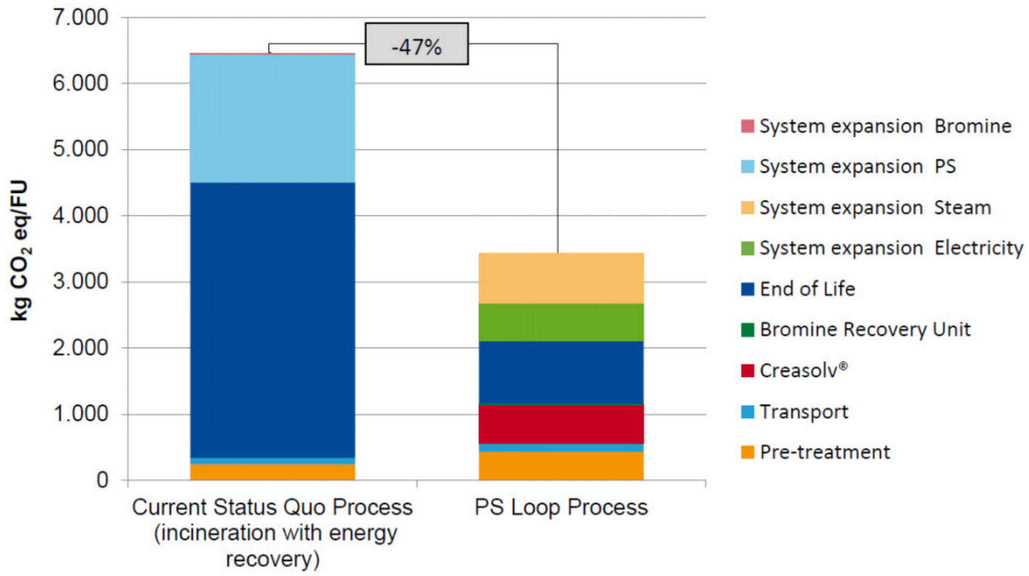

Figure 2. Climate Change in kg CO_2 eq/FU.

3. Waste Stream of Construction EPS Waste from Demolition Sites

Special attention has to be devoted to the waste stream to the PolyStyreneLoop demonstration plant, because the quality of the input material has an immediate effect on the quality of the output material. In addition, it is a crucial cost factor.

3.1. Collection and Pre-treatment

The material coming from demolition sites is collected and pre-treated by decentralized collection points, so-called HUBs. Most of the HUBs are managed by demolishers or recyclers with the necessary experience and network in the market. PolyStyreneLoop sources material only from certified HUBs. Making use of the cooperative model, only members of the cooperative can operate such a HUB.

PolyStyreneLoop requires certain input specifications regarding impurities of the material: HBCD content < 1.5 wt.%, water content ≤ 3 % and all other impurities ≤ 7 wt.% (PUR, mineral wool, cement, nails/iron and glue). Bituminous impurities are not allowed. As there are different applications for PS insulation such as ETICS or flat roofs with bituminous sheeting, the processes for deconstruction and waste treatment differ as well. A guideline for the collection and pre-treatment of PS foam waste is under preparation as part of the LIFE Grant requirements.

ETICS are widely used applications for the insulation of buildings. In Germany alone, it is estimated that between 1960 and 2012, 900 million m² of ETICS were installed of which, 80 % used EPS as insulation material. The complexity of the recycling of the EPS in ETICS lies in the fact that it is a composite of different materials such as adhesives, coating with reinforcing mesh and plaster. While the majority volume of ETICS is EPS, the insulation material itself only accounts for 10 % in terms of weight. Currently, Münster University of Applied Sciences and RWTH Aachen University are researching the necessary pre-treatment for ETICS for different utilisation processes such as PolyStyreneLoop. Through the crushing of ETICS with different stress loads, a selective pure EPS stream can be obtained. The universities are working on further optimizing the output through improved crushing. In a subsequent step, density-based sorting such as wind shifting can further concentrate the EPS fraction [16].

EPS Powerbrush [17] is a technology developed for cleaning EPS flat roof boards bond with bitumen sheets. At the demolition site the bitumen is removed by hand from the EPS boards. The bitumen is collected and follows a special recycling route. Then the EPS boards are stacked and transported to the pre-treatment plant. There the boards are sorted – to speed up the cleaning process – and fed to the EPS Powerbrush (maximum contamination 15 %). The outcome is clean EPS boards, free of bitumen, which can then be used for further recycling. The extracted impurities are finally burned. In 2014, the machine was already tested on a 6000 m² EPS flat roof.

Figure 3. EPS flat roof boards with bitumen leftovers before and after treatment [18].

3.2. Compaction

EPS is a lightweight material, because it consists of 98 % air, with a density of 11-30 kg/m³. This makes it easy to handle on a construction site, however to optimize transportation the material needs to be compacted after the pre-treatment. By compaction of the material to a density of 100-450 kg/m³ the volume is reduced by a factor 5-25.

The technology to compact EPS from demolition sites is already available and a number of manufacturers sell the necessary machinery. With mobile compactors HUBs can additionally offer the service to smaller recyclers or demolishers, which do not have the necessary machinery themselves. The temperature inside a screw compactor is a critical issue for EPS compaction, because the temperature of EPS rises during compacting. If the temperature of the material exceeds 90 °C, EPS can start to degrade. This is undesired for the quality of the polystyrene product and might lead to clogging in the screw mechanism.

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XPS has a slightly higher density of 30-50 kg/m³, but may not be compacted (or even broken) without a deep cool unit, if it contains (H)CFCs, as these would otherwise be emitted.

3.3. Storage and Transportation to PolyStyreneLoop Demonstration Plant
EPS needs to be compacted into briquettes with a weight between 15 to 50 kg for better handling. The compacted briquettes are then either stored in Big Bags or stocked on pallets, wrapped in PE shrink foil. The wrapping prevents the material to become wet, if storage takes place outside, and avoids any loose material spread in the environment.

Once HUBs have collected, pre-treated, compacted and stored sufficient material, full truck loads are transported to the storage location in Terneuzen. In order to have enough feed-stock once the demonstration plant is operational, PolyStyreneLoop is already storing material from its certified HUBs.

3.4. Notification and Permits
The European Waste Shipment Regulation (EC) No 1013/2006 [19] establishes procedures and control regimes for the shipment of waste. If waste is transported across borders, a notification needs to be submitted to the authority of the place of origin by the transporting company. This requires notification (annex IA) and movement documents (annex IB). Each waste transporter is required to follow this notification procedure.

4. Future Developments
The PolyStyreneLoop demonstration plant is expected to run a test phase until 2021. In the meantime the technical, economic and environmental viability will be assessed. After successful results the concept is set to be gradually rolled-out to other locations throughout Europe coping with the upcoming volumes of PS foam waste in the following 10 years.

For XPS recycling a deep cool unit has to be installed for collecting the (H)CFC's under the Montreal Protocol.

5. Conclusions
The goal of PolyStyreneLoop is to build a plant for recycling polystyrene (PS) foam in Terneuzen, Netherlands. It shall demonstrate the safe destruction of HBCD while recycling the valuable resources polystyrene and bromine and thus closing two loops and contributing to a circular economy.

PolyStyreneLoop is a physico-chemical recycling process based on the CreaSolv® Technology. PS foam waste is dissolved and the polystyrene recovered. Subsequently, the remaining impurities including HBCD are destroyed and the bromine is recovered. This process has already been included in the UNEP Basel Convention Technical Guidelines as a best available recycling technology to handle HBCD waste. The financial plan of PolyStyreneLoop predicts a repayment of the debt capital within a few years. A Life Cycle Assessment by TÜV Rheinland certifies the environmental benefits of the PolyStyreneLoop process versus incineration.

Decisive for the success of the project will be the availability of the input material in sufficient quantity and quality. A guideline for the collection and pre-treatment of PS foam waste is under preparation. Corresponding demolition and pre-treatment techniques are already in place, further innovations are expected in the near future. In order to facilitate economic transportation, compaction of the foam waste is essential. Certified decentralized collection points (HUBs) will make sure that certain input specification will be fulfilled to ensure a smooth operation. For the transportation of waste containing HBCD across borders, a permit is required.

In 2019 the PolyStyreneLoop demonstration plant will be built. It is funded by companies from the entire PS foam value chain, and has also attracted the support of a European LIFE Grant. The plant shall be operational by the end of 2019. If the technical, economic and environmental viability will be as expected, the concept is set to be gradually rolled-out to other locations throughout Europe.

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