EPS and XPS Recycling and Reuse

Industry Analysis and Implementation Strategy

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by

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Cover: Extruder Recycling Plant PS Loop

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Abstract

The construction industry faces significant challenges in managing the insulation material waste, expanded polystyrene (EPS) and extruded polystyrene (XPS) due to their low density, contamination issues, and the presence of hazardous flame retardants. This study investigates the feasibility and environmental impact of different end of life methods for EPS and XPS waste contaminated with various construction materials, including glue and mortar as well as bitumen. A practical approach is taken, aiming to tailor existing recycling technologies to the specific needs and constraints of construction practices, thereby increasing the industry's recycling rate and reducing its environmental footprint. This work explores the entire lifecycle of EPS and XPS, from production and application to waste generation and recycling, and proposes solutions. By focusing on practical solutions and industry-specific needs, this work facilitates a shift towards a more circular and sustainable model for EPS and XPS waste management in the construction industry, offering actionable recommendations for construction companies and waste managing companies to adopt more environmentally responsible practices.

Summary

Expanded polystyrene (EPS) and extruded polystyrene (XPS) are versatile materials widely used in the construction industry for insulation. However, their production and disposal raise significant environmental concerns.

The environmental concerns associated with EPS and XPS waste, derived from petroleum, have underscored the need for sustainable waste management practices.

Here, the production processes, applications, waste types, and recycling technologies for EPS and XPS are examined, and the evolution of blowing agents and flame retardants towards more sustainable alternatives are highlighted.

Additionally, innovative recycling strategies are proposed for various types of EPS and XPS waste, including off-cuts, demolition waste contaminated with glue and mortar, and bitumen contaminated material. These strategies aim to minimize the environmental impact of EPS and XPS waste and promote a circular approach in the construction industry.

To assess the feasibility and sustainability of these recycling strategies, an environmental and economic analysis is conducted. This analysis makes use of Life Cycle Assessment (LCA) to evaluate the environmental impact as well as Life Cycle Cost Assessment (LCCA) and Circular Economy Index (CEI) to analyze the economic aspects. The results of this analysis provide valuable insights into the environmental benefits and cost-effectiveness of the proposed recycling practices.

Nomenclature

CEI - Circular Economy Index
CFC - Chlorofluorocarbons
CRD - Construction, Renovation, and Demolition
DSC - Differential Scanning Calorimetry
EPD - Environmental Product Declaration
EPS - Expanded Polystyrene
ETICS - External Thermal Insulation Composite Systems
FTIR - Fourier-Transform Infrared Spectroscopy
HBCD - Hexabromocyclododecane
HCFC - Hydrochlorofluorocarbons
HFO - Hydrofluoroolefins
ICF - Insulated Concrete Forms
LCA - Life Cycle Assessment
LCCA - Life Cycle Cost Assessment
LCI - Life Cycle Inventory
LCIA - Life Cycle Impact Assessment
PBT - Persistent, Bioaccumulative, and Toxic
POP - Persistent Organic Pollutant
PP - Polypropylene
PS - Polystyrene
PVC - Polyvinyl Chloride
REACH - Registration, Evaluation, Authorisation and Restriction of Chemicals
RFID - Radio Frequency Identification
SEM - Scanning Electron Microscope
SIP - Structural Insulated Panels
SVHC - Substance of Very High Concern
VCL - Vapor Control Layer
WDVS - Wärmedämmverbundsystem (German term for ETICS)
XPS - Extruded Polystyrene

Contents

1
Introduction

This work aims to develop sustainable and cost-effective methods for managing expanded polystyrene (EPS) and extruded polystyrene (XPS) insulation waste by recycling or reusing the waste in the construction industry. It seeks to diminish the gap between known technologies in research and practical application by exploring pain points, current waste flows and recycling strategies of EPS and XPS waste and make them applicable for the construction industry. The study involves investigating techniques applicable for industry practices and finally proposing a set of processes showing their environmental and ecological impact.

1.1. Polystyrene Challenge in Construction Waste Management

The construction, renovation and demolition (CRD) industry, a major generator of waste, is full of polystyrene materials, particularly in insulation applications. These large waste volumes necessitate innovative, sustainable and economic viable solutions to mitigate their environmental impact.

As the construction industry continues addressing the complexities of waste management, particularly in CRD waste, polystyrene foam such as EPS and XPS emerges as a prominent contributor to environmental challenges. As EPS and XPS represent a significant portion of the environmental plastic waste challenge, with an astonishing amount ending up in the oceans due to its notably low recycling rate. This problem is intensified by the 3 million tons of polystyrene waste that threatens ecosystems due to its resistance to natural degradation processes [1; 2; 3; 4]. The recycling of EPS and XPS is particularly problematic due to its composition — over 95% air — making it a bulky and expensive material to process and handle efficiently [5].

Reflecting on EPS's and XPS's historical context, their widespread use dates back to the 1970s, following their development from polystyrene, a polymer discovered in 1839. EPS's and XPS's superior insulating properties facilitated their adoption in construction applications such as Structural Insulated Panels (SIPs), Insulated Concrete Forms (ICFs), and External Thermal Insulation Composite System (ETICS), where they are known for its ability to significantly reduce energy costs [6]. Starting in the 1970s, EPS's remarkable insulation properties were highly valued for their ability to mitigate temperature fluctuations and reduce heating costs. However, the environmental impact was not a primary consideration during its initial design and widespread adoption. Today, being a fully petroleum-based and largely non-recycled material, EPS and XPS present environmental challenges that necessitate a reevaluation and adaptation of their production and use.

In the current environmental and economic climate, the preference for incineration over recycling is influenced by immediate cost savings, despite the potential long-term benefits of material recovery and reuse. Polystyrene's high energy content, similar to that of oil, makes it attractive for incineration but often discourages recycling, raising concerns about the sustainability of this practice.

The narrative of polystyrene's role in the construction sector highlights a critical point: the industry must transition towards sustainable waste management, increasing the recycling rate of polystyrene to mitigate its environmental footprint. Embracing this shift is essential to protect ecosystems and promote a circular economy, where materials like polystyrene are not merely used and discarded but are seen as valuable resources to be reclaimed and repurposed.

Research Context

In both the Netherlands and Austria, buildings are commonly insulated with materials such as EPS and XPS, which are integrated to their insulation systems.

The widespread use of EPS and XPS in construction has led to significant waste management challenges. Recycling EPS and XPS is often financially unviable. As a result, many construction companies and waste managing companies do not post process in an environmentally satisfying way. Improper disposal of these materials contributes to environmental pollution, similar to the issues posed by plastic waste. This leads to effects on wildlife and may pose risks to human health through contamination [7] .This work aims to investigate and develop methods for a construction company to economically reuse and recycle EPS and XPS waste, thereby addressing both environmental and economic concerns.

1.2. Recycling Challenges in the Construction Sector

The global construction sector faces a pressing challenge in the CRD plastic waste management. Landfill disposal and incineration continues to be the prevailing practices, a status quo maintained by a lack of precise recycling directives, not existing incentives, and insufficient knowledge about recycling processes within the industry. Such practices not only hinder the transition to a circular economy but also perpetuate reliance on non-renewable crude oil sources. [8]

The potential to recycle these plastics exists; however, the reality of the situation reveals a different picture. Contamination of materials, complex sorting necessities, and the potentially reduced value derived from the recycled output contribute to the economic unviability of the recycling operations. This is further complicated by market development barriers such as the high levels of impurities, the challenging task of extracting plastics from mixed garbage, and the competitive disadvantage of recycled plastics against their virgin counterparts. The latter often succeeds due to their uniform quality and cost-efficiency, posing a significant challenge to the uptake of recycled materials in the industry [8].

Research Problem

This work explores the gap between academic exploration and practical application in the management of EPS and XPS waste within the construction industry. While academic studies have shed light on various technologies and methods for handling EPS and XPS waste, their transition from theoretical frameworks to real-world implementation in the construction sector has been limited. This research is a cooperation with the construction company FREY Bauunternehmen (FREY) in Austria and aims to find out how tested technologies can be implemented in practical scenarios. Previous academic research has introduced a range of potential solutions for EPS and XPS waste management. However, these solutions often remain confined to the domain of theory or are tested in controlled environments, lacking real world application in the construction industry. This gap highlights the need for a focused study on how these theoretical findings can be translated into effective, practical applications.

1.3. Research Question, Objectives and Approach

The key research questions and objectives aimed at addressing the challenges identified through sector-specific challenges and plastic waste impacts. By focusing on transformative approaches to EPS and XPS waste, the work establishes practical solutions that significantly improve waste management practices in the construction industry. The questions and objectives outlined below will guide the work to discover methods that not only reduce environmental harm but also improve economic outcomes.

Main Research Question

How can innovative approaches in recycling and reusing EPS and XPS waste transform the sustainability and increase cost efficient practices of construction industry?

Sub-Questions:

1. Material Property Characteristics: What are the properties of EPS and XPS waste that pose challenges to recycling, and how do these properties influence the choice of recycling methods and potential applications for recycled materials?
2. Potential for Repurposing EPS and XPS: What are the most promising methods for transforming EPS and XPS waste into viable construction materials, and which construction applications are best suited for their integration?
3. Evaluating Current Recycling and Reuse Practices: In what ways are EPS and XPS currently recycled and reused within the construction industry, and what improvements or modifications can be made to align these practices with the needs of the construction company?
4. Waste Stream Characteristics and Management Strategies: How do the diverse characteristics of EPS and XPS waste streams generated at construction sites influence waste management strategies, including separation, collection, and preliminary processing?
5. Technical and Logistical Aspects: What specific technologies and processes are necessary for effective processing of EPS and XPS, and what are the logistical challenges and solutions in implementing these processes at construction sites?
6. What are the environmental impacts of implementing recycling transformation methods for EPS and XPS, and how can a construction company benefit economically, as evaluated through a Life Cycle Assessment and Life Cycle Cost Analysis?

Research Objectives

The primary objective of this research is to improve the sustainability and economic efficiency of handling EPS and XPS waste in the construction industry. This will be achieved through:

1. Evaluating Waste: Examining EPS and XPS waste characteristics at construction sites and identifying current practices for waste handling and processing.
2. Investigating Reusability: Assessing methods for reusing and repurposing EPS and XPS waste into construction materials, and analyzing current recycling practices within the industry.
3. Propose Recycling Processes: Advice innovative recycling methods for EPS and XPS waste and integrating these processes into the construction sector to support circular economy principles.
4. Environmental Impact and Economic Assessment: Conducting a Life Cycle Assessment and Life Cycle Cost Analysis to evaluate the environmental implications of the proposed recycling strategies. The life cycle assessment will focus on the difference between current practices and the proposed solutions.

The core objective of this study is to assess the viability of technologies for FREY and also other companies. It seeks to determine which of these methods can be feasibly and effectively applied within the construction industry, thereby providing a practical dimension to implement scaled applications and academic research. By doing so, the study aims to not only enhance waste management practices in the construction industry, making them more sustainable and cost-effective, but also to contribute to the academic discourse. This contribution is offering new insights into how theoretical research can be grounded in practicality, enriching the existing body of knowledge with findings that have direct applicability and impact in the construction sector.

Research Approach

This research takes a comprehensive approach to understanding the end-of-life scenarios of EPS and XPS in the construction industry. It begins with a thorough analysis of current production methods and applications of EPS and XPS within the construction sector, evaluating their implications for end-of-life waste streams and contamination levels. The study then explores existing EPS and XPS recycling technologies, examining their current utilization and potential within the industry.

This exploration involves a theoretical review of existing literature, a market research and the analysis of recycling challenges. The practical market research is conducted with key industry stakeholders in both Austria and the Netherlands, including producers, consultants, construction firms, waste management

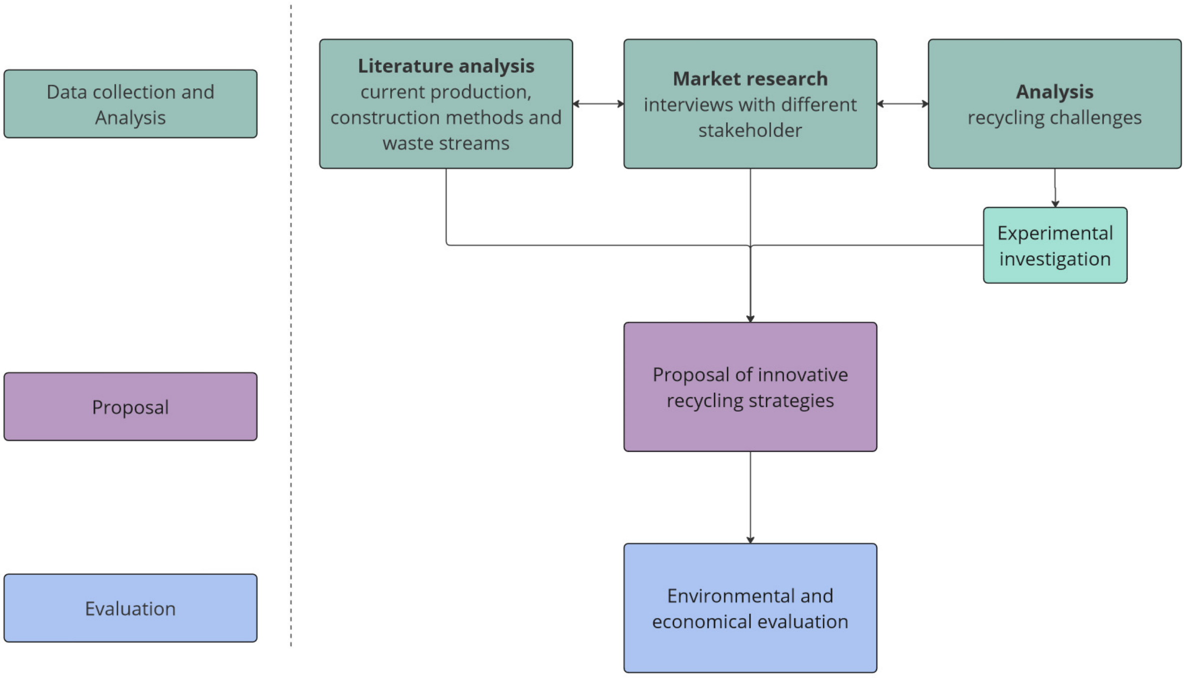


Figure 1.1: Research approach

companies, waste treatment companies, recycling facilities, and incineration facilities. These insights provide a comprehensive overview of the current market landscape and challenges.

To address the identified challenges in separating EPS and XPS from other waste streams, a focused experimental investigation is included. This experiment sheds light on the specific issues faced during separation and informs the development of targeted solutions.

Based on these analyses, the research proposes a range of innovative handling methods for contaminated EPS and XPS, along with strategic advice and recycling strategies aimed at improving material recovery and reuse. These proposed strategies, informed by the specific challenges and opportunities identified, are evaluated from both an environmental and economic standpoint. This evaluation encompasses a life cycle assessment to quantify the potential environmental impacts of each strategy. In addition, a detailed cost analysis to determine their financial feasibility is added. By considering both the ecological and economic dimensions, this research aims to provide decision-makers and industry stakeholders with a understanding of the trade-offs and benefits associated with each proposed solution, facilitating the adoption of more sustainable and effective waste management practices for EPS and XPS within the construction industry.

2

Production, Waste Type, Application, and Recycling

Expanded polystyrene (EPS) and extruded polystyrene (XPS) are widely used insulation materials in construction. This chapter begins by examining the existing literature on the background of plastics, highlighting the critical impact of plastic waste in the construction industry. It then discusses the production processes and properties of EPS and XPS, detailing how their distinct characteristics lead to diverse applications in construction. These varied applications, generate specific waste streams, which are examined in detail. The chapter further explores how current literature addresses the repurposing of EPS and XPS waste, including potential applications and the theoretical basis for recycling these materials. Furthermore the associated recycling possibilities in literature are presented. By providing an overview of EPS and XPS literature, from production to waste management, this chapter lays the groundwork for further investigation into innovative recycling solutions and their potential to transform waste into valuable resources.

2.1. Background on Plastics

The substantial role of the construction industry in Europe's waste generation, particularly plastics like EPS and XPS, necessitates a detailed analysis of waste management strategies.

Given that in 2020, the european union (EU) generated 2,135 million tonnes of total waste, equating to 4,815 kg per capita. Remarkably, 37.5% of this waste came from construction and demolition, with even higher proportions in the Netherlands (65.4%) and Austria (76.5%). Between 2004 and 2020, there was a 12.4% increase in construction waste in Europe, contrasting with decreasing waste generation in sectors like energy and manufacturing [9].

To address the specific challenges associated with EPS and XPS in the construction industry's waste management, a detailed analysis of the european plastics industry's recent data is necessary. In 2021, european plastic production, including recycled materials, totaled 57.2 million tonnes. In figure 2.1, polystyrene (PS) and EPS accounted for 6.1% of this production, underscoring their significant utilization within the construction sector [10].

The total demand for plastics in europe, excluding recycled production, stood at 50.3 million tonnes in 2021, with the construction sector alone accounting for 21.3%. The Netherlands and Austria demonstrated considerable usage patterns within this framework: 4.2% - 2,11 million tonnes - of europe's total plastic demand originated from the Netherlands, and 2.1% - 1.05 million tonnes - from Austria, indicating their significant engagement with plastic materials, including EPS and XPS, in construction [10].

Further analysing the plastics market, it's observed that 1.6% (2021) — or 0.8 million tonnes — of the total european plastic production excluding recycling which consists of 50.3 million tonnes was specifically polystyrene expanded (PS-E), this includes both EPS and XPS materials . The subset

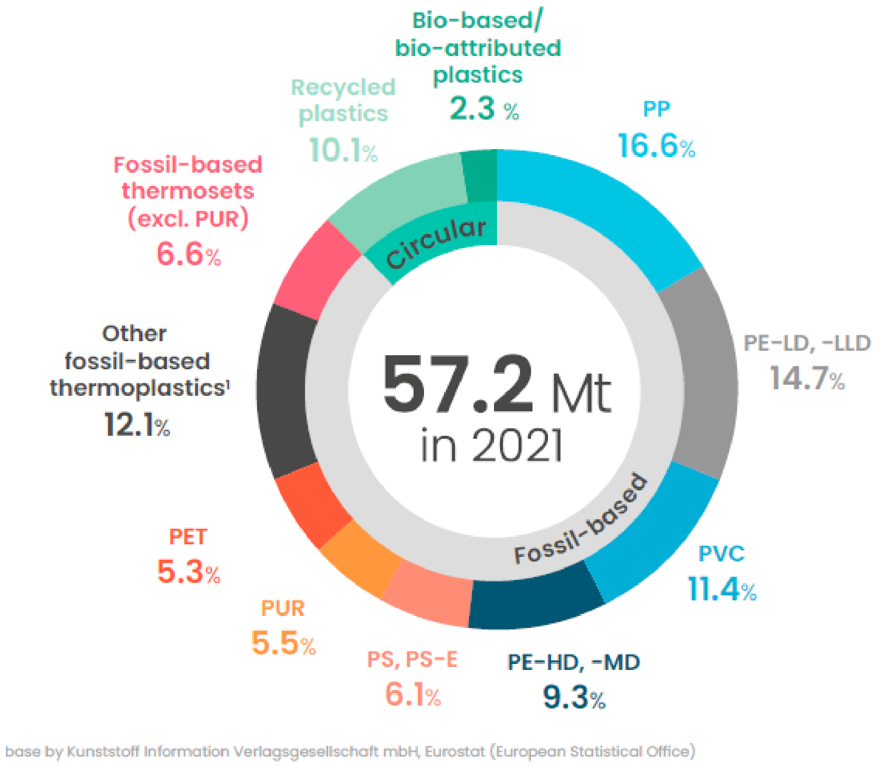


Figure 2.1: European plastic production [10]

highlights the specific contribution of these materials to the overall plastic production and their relevance in construction applications. This can be also seen in figure 2.2 [10].

This ongoing scenario emphasizes the critical need for advanced recycling technologies and strategies, particularly for managing XPS and EPS waste in the construction industry. Despite considerable research, the practical application of these technologies in real-world settings, such as those at companies like FREY, has been limited. There remains a significant gap between theoretical research and practical implementation, reflecting the broader challenges within the european construction sector, illustrated by the increasing volume of construction waste and the substantial proportion of plastics involved.

Given these insights, strategic developments in waste management are essential, especially for addressing the nuances related to EPS and XPS within the construction industry. The push towards implementing effective and economically viable recycling solutions is not only beneficial for environmental sustainability but also important for ensuring the long-term viability of the construction sector in europe.

Looking back at earlier data for a broader perspective, in 2020, the Netherlands generated 1,698 kilotonnes (kt) of plastic waste, with 72 kt categorized as construction waste, incorporating residuals amounting to 4.2% of the plastic waste stream. This marked a significant portion of plastic waste from construction activities, underlining the urgent need for efficient waste management practices [11]. In 2015, Austria produced 916 kt of plastic waste, with substantial quantities stemming from construction activities. Specifically, the construction sector produced 30 kt of plastic waste, half of which were rigid materials from construction debris such as plastic windows and pipes [12]. These historical figures solidify the ongoing challenges and necessitate robust solutions in managing construction industry waste effectively.

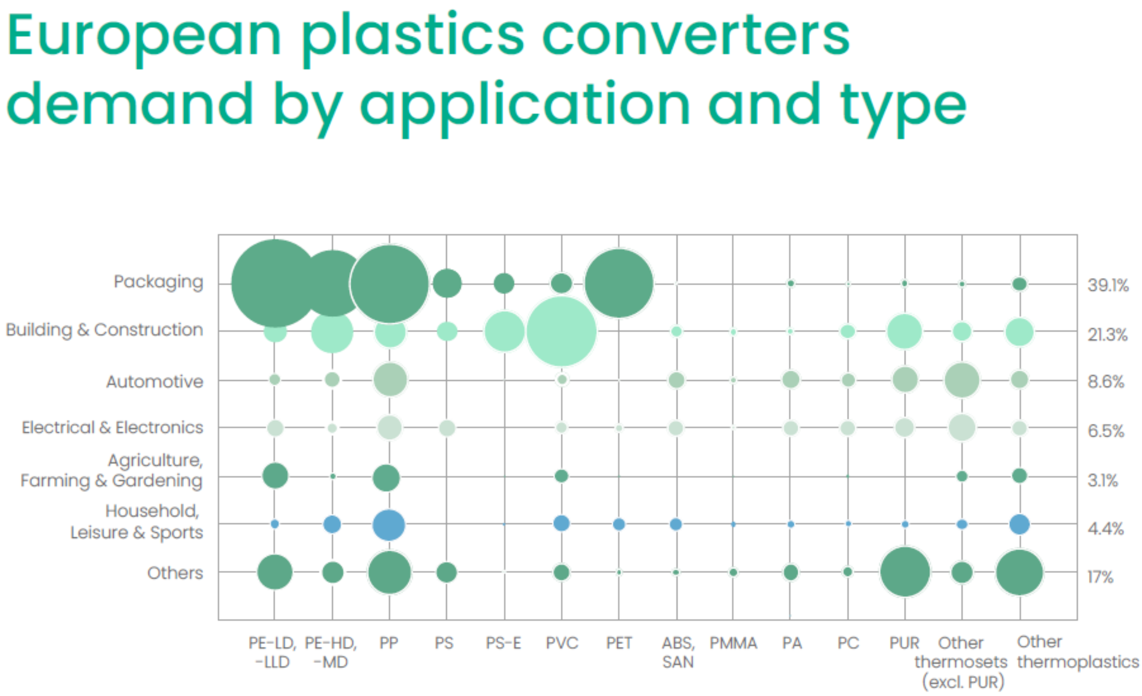


Figure 2.2: European plastic, type and application[10]

2.2. Production of Polystyrene Products EPS and XPS

The production of polystyrene products, specifically expanded polystyrene (EPS) and extruded polystyrene (XPS), encompasses complex chemical and physical processes tailored to meet high industry standards for functionality and environmental safety. Understanding these processes is important for evaluating how the materials can be separated and recycled effectively, a key aspect in the ongoing effort to enhance sustainability in construction materials.

2.2.1. Production of EPS

EPS production begins with the creation of styrene monomer, derived from petroleum and natural gas byproducts. This monomer is then transformed into long chains of polystyrene through a chemical reaction called polymerization. To enhance fire safety, particularly for applications in the construction industry, fire retardant substances are often incorporated during this polymerization step. Traditionally, Hexabromocyclododecane (HBCD) was the primary choice due to its effective fire-retardant properties. However, growing environmental and health concerns led to its phasing out and replacement with safer alternatives like PolyFR, which offers comparable fire resistance without the associated risks. The resulting expandable polystyrene beads, now infused with fire retardant, undergo further processing to achieve their final form [13].

A critical step in making EPS is the expansion phase, where solid polystyrene beads are mixed with a blowing agent, mainly pentane today. Pentane is chosen for its low environmental impact, a significant improvement over older agents like chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), which harmed the ozone layer and increased greenhouse gases. In the expansion stage, steam heats the beads, causing the pentane to vaporize and the beads to expand up to 50 times their original size. This expansion is finely controlled to achieve consistent bead density and size, essential for the quality of the final EPS product [13].

After expanding, the beads are cooled and stabilized, allowing them to keep their new size and prepare for the next stage. In the molding phase, the expanded beads are placed into molds and heated again with steam. This additional expansion and heating cause the beads to fuse into a solid form, resulting in the finished EPS product. This method allows EPS to be made in various shapes and sizes, used in everything from packaging and insulation to building materials [14].

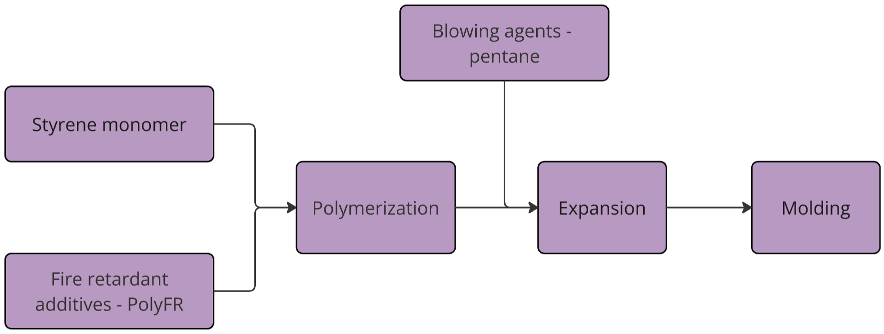


Figure 2.3: EPS production

2.2.2. Production of XPS

The manufacturing process of extruded polysterene (XPS) foam insulation is finely tuned to produce a product to meet the high insulation, moisture content and durability standards required in modern construction.

The process begins with the careful selection of high-quality polystyrene granules which are almost like powder. These granules are blended with a variety of performance-enhancing additives, including fire retardants. Traditionally, hexabromocyclododecane (HBCD) was used for its effectiveness; as mentioned earlier, due to environmental and health concerns, it has been largely phased out in favor of PolyFR, a safer alternative that provides comparable fire resistance without the associated environmental risks [15].

Alongside these additives, environmentally friendly blowing agents such as carbon dioxide (CO_2) and hydrofluoroolefins (HFOs) are incorporated into the mixture. These agents are critical as they influence the foam's expansion and insulation properties while minimizing ecological impact. This shift from older, harmful chemicals to greener alternatives marks a significant advancement in reducing the ecological footprint of XPS production .

During the extrusion phase, the blend of polystyrene granules, fire retardants, and blowing agents is fed into an extruder. Inside this apparatus, a rotating spiral screw propels the mixture forward, exposing it to high heat and pressure. This causes the polystyrene granules to melt and plasticize, transforming into a viscous liquid. The continuous mixing and shearing action within the extruder ensures the even distribution of additives and the thorough dispersion of the blowing agent into the viscous liquid.

As the viscous liquid reaches the end of the extruder, it is injected with additional blowing agents under precisely controlled high-pressure conditions. The mixture is then forced through a specifically shaped die, and upon exiting the die into a low-pressure environment, the blowing agents rapidly volatilize, or turn into gas. This sudden expansion of gases causes the viscous liquid to increase in volume and form countless tiny bubbles. As the liquid cools and solidifies, these bubbles become the closed cells that give XPS its characteristic insulation properties.

As this foamy mixture exits the expansion process, it begins to cool and solidify, taking on its final form. The cooling phase is meticulously controlled to ensure that the material expands to the correct dimensions and solidifies with the desired closed-cell structure, essential for optimal insulative properties.

Once the material is extruded, it is cut and trimmed into boards or panels, which are then further processed depending on their intended application. This may include the addition of laminated layers for moisture protection or edge modifications to facilitate easier installation [15].

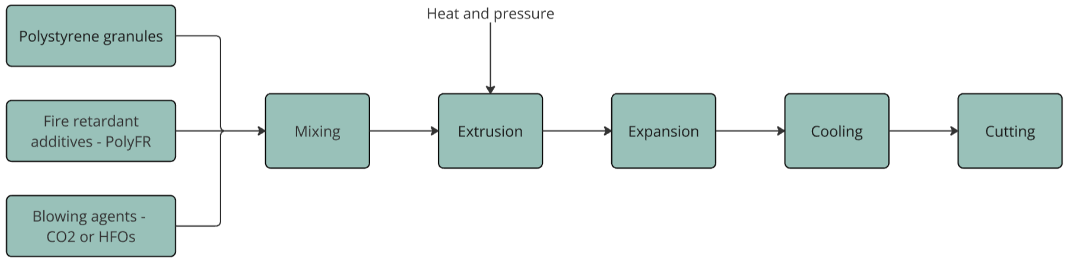


Figure 2.4: XPS production

2.2.3. Differences between EPS and XPS

Table 2.1 presents a detailed comparison of EPS and XPS, focusing on various aspects of their production and properties. Both materials originate from polystyrene but differ significantly in their manufacturing processes, which affect their physical characteristics, properties seen in table 2.2 and applications.

EPS starts with polymerized styrene beads that are expanded using steam in a two-stage process and molded to form lightweight structures with beads fused together. This method results in a material with lower moisture resistance and compressive strength, making it suitable for insulation and packaging applications where lower loads are expected.

In contrast, XPS is produced through a continuous extrusion process, combining high heat and pressure to melt polystyrene mixed with additives and eco-friendly blowing agents such as CO_2 or HFOs. This process creates a uniform, closed-cell structure that offers higher compressive strength and moisture resistance. Thus, XPS is preferred for high-load applications such as foundation slabs and areas prone to moisture.

Both EPS and XPS have evolved to incorporate more environmentally friendly practices, including the use of eco-friendlier blowing agents and improved fire retardants to reduce environmental impact. The following table captures these comparative aspects, emphasizing the specific applications and environmental focus of each material.

Feature	**EPS**	**XPS**
Raw material	Polymerized styrene beads	Mixed polystyrene granules
Blowing agent	Pentane (earlier CFCs, HCFCs)	CO_2, HFOs (earlier HCFCs)
Process	Two-stage expansion with molds	Continuous extrusion
Structure	Beads fused together, lighter	Uniform, closed-cell, denser
Moisture resistance	Lower	Higher
Compressive strength	Lower	Higher
Typical applications	Insulation, packaging	High-load insulation, moisture-prone areas
Environmental focus	Eco-friendlier agents, improved fire retardants	Eco-friendlier agents, improved fire retardants

Table 2.1: Comparison of EPS and XPS production and properties

2.2.4. Properties of EPS and XPS

Building on the understanding provided in table 2.1, which focused on the production processes and general properties of EPS and XPS, this subsequent table shows the technical specifications of each material. It aims to provide a granular view of their technical data, which is critical for professionals in the field of construction and building insulation to evaluate their specific suitability for various applications.

Table 2.2 compares the properties of two specific products: EPS (Sto-Dämmplatte Top32) [16] and XPS (Sto-Dämmplatte XPS 300 SO) [17]. It highlights key technical attributes such as density, thermal conductivity, tensile strength, vapor diffusion resistance, and water absorption, among others. These parameters are vital for understanding how these materials perform under different environmental conditions and stress factors.

Further, table 2.2 also mentions the fire behavior and processing techniques for both materials, providing insights into their safety characteristics and ease of installation. Special features related to environmental impact and resistance properties are also discussed, which are increasingly important in sustainable building practices. This detailed comparison facilitates a better understanding and evaluation of the specific application domains and performance criteria of both materials within the field of construction and building insulation.

Feature	**EPS (Sto-Dämmplatte Top32) [16]**	**XPS (Sto-Dämmplatte XPS 300 SO) [17]**
Material type	Expanded polystyrene foam	Extruded polystyrene foam plate
Density (kg/m³)	> 17	≥ 30
Thermal conductivity (W/(m·K))	0.032	0.035 (10-60 mm), 0.036 (≥ 70 mm)
Tensile strength (MPa)	>= 0.08	Not specified
Vapour diffusion resistance	20/50	250 - 80
Specific heat capacity (Wh/(kg·K))	Not specified	0.39
Water absorption (Vol.-%)	< 0.02 (by area)	≤ 0.7 (prolonged immersion), ≤ 5 (by diffusion)
Fire behavior	Difficult to ignite (Euroclass E according to EN 13501-1)	BKZ 5.1
Special features	Shrink-free, free of (F)CFCs and HFCKWs	CFC and HCFC-free, UV-sensitive, not resistant to solvents

Table 2.2: Comparison of technical data of EPS and XPS

2.2.5. Evolution of Production Due to HBCD Regulations

The recycling of polystyrene foam, specifically EPS and XPS, has encountered substantial regulatory challenges in recent years. The requirement for these materials to contain flame retardants has been complicated by the changes surrounding the use of hexabromocyclododecane (HBCD), a once prevalent flame retardant. With global market shares exceeding 95%, HBCD's dominance was unrivaled in the construction sector [18]. However, due to environmental and health concerns associated with its persistent, bioaccumulative and toxic PBT properties, the EU took decisive action by labeling HBCD as a substance of very high concern in 2008, which led to its inclusion in annex XIV of the REACH regulation [19] in 2011, effectively requiring authorization for its use [18].

A significant milestone occurred on May 9, 2013, when HBCD was added to annex A of the Stockholm convention's [20] list of persistent organic pollutants, signaling an international agreement to phase out its production and use [21]. Though the EU had permitted a time-limited exemption for the production and use of PS foams in construction, the global direction was clear—HBCD would no longer be a viable option in the near future [18].

In response to these legal developments, the industry has introduced a new polymeric flame retardant (PolyFR) to replace HBCD in PS foam applications. Despite this innovation, the legacy of HBCD will persist in construction and demolition waste for the next two to five decades due to its previous widespread application [18].

Current legislation mandates that waste containing HBCD must be destroyed or returned to its roots and is not allowed to be further used in any other application. However, emerging discussions propose a more sustainable method, advocating for the separation of HBCD from the polystyrene matrix. This process would not only enable the recovery of clean, flame retardant-free polystyrene but also allow the repurposing of the separated flame retardants as a secondary source of bromine, pending suitability for recovery technologies [18].

A historical overview provides insights on the development of HBCD.

Before the Ban

- **Prior to 2008**: HBCD was extensively used as a brominated flame retardant in EPS and XPS, primarily for insulation materials in construction due to its effectiveness in enhancing fire resistance [22].
- **Global Use**: HBCD enjoyed a dominant position in the market, with its use in EPS and XPS foams for building and construction applications achieving global market shares higher than 95% [22].

Identification and Regulatory Actions

- **2008**: The EU identified HBCD as a substance of very high concern (SVHC) due to its persistent, bioaccumulative, and toxic (PBT) properties [18].
- **2011**: HBCD was included in annex XIV of the REACH regulation, marking it for authorization under the EU's chemical management program. This inclusion signaled the beginning of regulatory scrutiny and the eventual phase-out of HBCD [21].
- **May 9, 2013**: HBCD was added to annex A (Elimination) of the Stockholm convention's list of persistent organic pollutants (POPs). This inclusion meant a global acknowledgment of the need to ban the production and use of HBCD, marking a significant step towards its phase-out [21].
- **Post-2013**: Following its listing under the Stockholm convention, countries began to implement measures to eliminate the use of HBCD, transitioning towards safer alternatives for flame retardancy in polystyrene foams [18].

Transition and Current Status

- **2014/2015**: By this time, the use of HBCD in construction applications was under stringent regulation, with the EU requiring PS foams for construction to be equipped with alternative flame retardants. A special polymeric brominated flame retardant (PolyFR) was developed to replace HBCD in PS foam applications [18].
- **Current**: The phase-out of HBCD has led to significant research into and development of recycling technologies capable of removing HBCD from waste EPS and XPS. The CreaSolv® process, which is going to be elaborated in chapter 3, represents an advanced solvent-based recycling technique that not only recovers polystyrene for reuse but also effectively removes HBCD, ensuring that recycled PS meets safety and environmental standards [22].

Implications and Future Directions

- **Waste management**: The transition away from HBCD and the development of recycling technologies like the CreaSolv® [23] process are critical for managing the substantial amounts of HBCD-equipped EPS and XPS still in use or entering the waste stream [18].
- **Regulatory impact**: The ban on HBCD has spurred innovation in flame retardant technologies and recycling processes, reflecting a broader trend towards sustainability and environmental protection in chemical management and waste treatment [22].
- **Circular economy**: The efforts to recycle HBCD-containing polystyrene foam into clean, usable PS granules align with the principles of the circular economy, aiming to minimize waste and resource consumption while promoting the reuse of materials [22].

The ban of HBCD exemplifies the complex interplay between environmental regulation, material science, and waste management practices, highlighting the challenges and opportunities in transitioning towards more sustainable materials and technologies [21].

2.3. Different Insulation Applications and Waste Streams

EPS and XPS have been widely used insulation materials in the construction industry since the 1970s due to their thermal properties, versatility, and cost-effectiveness. They quickly gained popularity for their ability to reduce energy costs and have been consistently used and appreciated to this day. The material finds application in various areas, from wall and roof insulation to moisture-prone areas like damp walls and foundations. However, the use of these materials generates diverse waste streams throughout their lifecycle, posing challenges for recycling and reuse.

This analysis explores the different waste streams originating from EPS and XPS insulation materials used in construction, categorizing them by source, application, and level of contamination. It examines the impact of contamination on the recycling and reuse potential of these materials, focusing on the challenges posed by adhesives, mortar, and bitumen.

Understanding the diverse nature of these waste streams is necessary for developing effective strategies to address the challenges associated with their recycling and reuse.

2.3.1. Analysis of Insulation Application

This analysis underscores the necessity for a nuanced understanding of waste streams in the construction industry. Particularly the implications of contamination levels on recycling and reuse opportunities. By categorizing and closely examining these streams, we can identify more sustainable waste management and material recovery strategies.

The specific waste materials generated by FREY, highlights the diversity of waste streams originating from different applications and stages of insulation material utilization. The company categorizes its waste primarily into three distinct streams, each characterized by the material type, application, and level of contamination:

Fresh EPS and XPS off-cut waste from construction sites: Represents unused EPS and XPS materials, which are either surplus or off-cuts not fitting any specific construction requirement. This category exhibits the lowest level of contamination, as these materials have not been utilized on-site.
EPS and XPS used in wall insulation: This stream includes EPS and XPS that has been applied to walls. EPS typically contaminated with glue, mortar and a connecting mesh and XPS utilized in moisture-prone areas such as damp walls and foundations, also contaminated with glue, mortar and a connecting mesh.
EPS for roof insulation: In this application, EPS is often contaminated with a bitumen layer designed to waterproof the surface.

The level of contamination significantly influences the feasibility of recycling or reusing these materials. Particularly, materials contaminated with adhesives, glue and mortar, or bitumen present considerable challenges in recycling processes. The following paragraphs take a closer look into these waste streams.

2.3.2. Uncontaminated Construction Site Waste - Off Cuts

The least contaminated material within the waste streams is what remains unused on construction sites. This category comprises offcuts and surplus EPS and XPS insulation materials, which are either not required or do not fit into the construction design. Typically, these pieces are collected in construction waste containers. Research and site visits, including interactions with experts in the field, producers of EPS and XPS, and examinations of construction practices in Delft, reveal that approximately 7% of produced insulation material ends up as waste without being used. Given its minimal to non-existent contamination levels, this fraction of material presents a significant opportunity for reintroduction into the production cycle, underscoring the potential for enhanced recycling and reuse practices.

However, not all waste streams are as easily recyclable. The following sections will focus on the more challenging waste streams, where contamination with glue, mortar, and bitumen poses significant barriers to recycling.

2.3.3. EPS and XPS Demolition Waste - Contaminated with Glue and Mortar

In Austria, External Thermal Insulation Composite Systems (ETICS), often referred to as "Wärmedämmverbundsystem (WDVS)," have been widely used for exterior insulation since the 1960s. As these systems reach the end of their service life, their demolition generates a significant amount of waste, posing challenges for recycling.

ETICS are multi-layered constructions consisting of various materials with diverse chemical properties (figure 2.5). These systems must adhere to national and european construction regulations and are typically implemented as complete systems from certified providers.

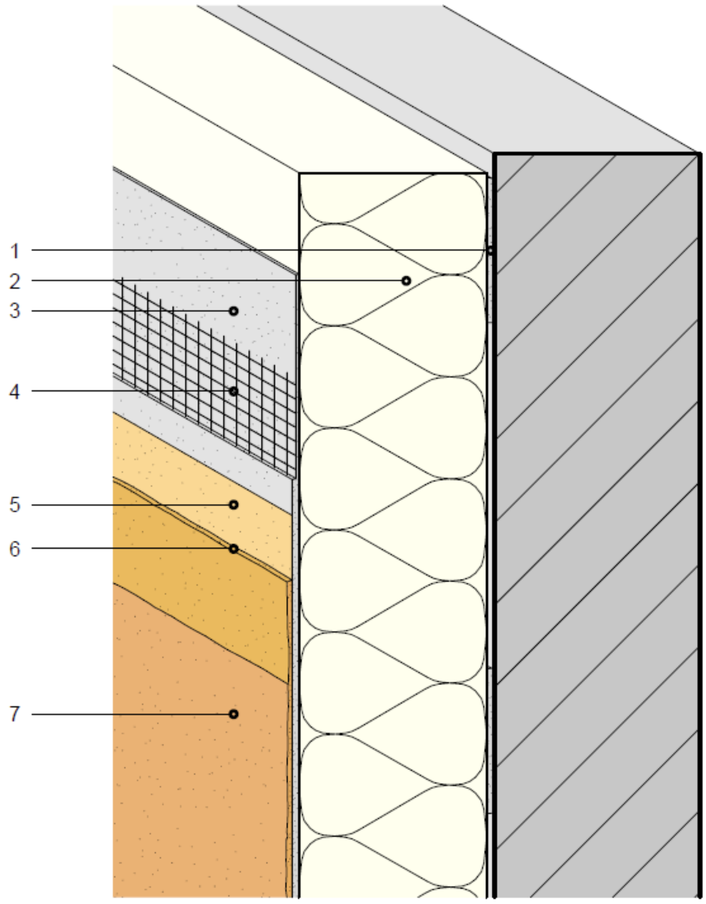


Figure 2.5: Wall structure with ETICS [24]

The main components of ETICS as seen in figure 2.5 and as per EN 13499 [25] and DIN 55699 standards, include:

1. Adherence: Adhesives or mechanical fasteners used to attach EPS or XPS boards to the wall.
2. Insulation: EPS or XPS boards for thermal insulation.
3. Armoring layer: Base coat render, typically cement-based, applied over the insulation for protection and reinforcement.
4. Armoring mesh: Alkali-resistant glass fiber or plastic mesh embedded in the armoring layer for added strength.
5. Plaster and finishing layers: Thin layer of mineral or polymer-based plaster for weather protection and aesthetics, often with decorative finishes.

The complexity of these layers and the use of different materials make the separation and recycling of ETICS components a significant challenge, hindering the recovery of valuable resources like EPS and XPS. To elaborate on the challenges of separating and recycling EPS and XPS from ETICS, a closer look at the materials and application methods used in these systems is necessary.

ETICS - Materials and Application

EPS and XPS waste contaminated with glue and mortar is primarily utilized for wall insulation as part of ETICS. The contamination usually consists of adhesive on the interior side and a cement-based mortar with an armoring mesh on the exterior side, as detailed in figure 2.5. The adhesive, applied either directly to the wall or the insulation material, can be mineral-based (cement, sand, additives) or dispersion-based (polymeric binders) [26]. Common application methods include full-surface, perimeter-adhesive-dot, and the bead method [27].

The bonding strength of glued ETICS must adhere to regulatory standards, with a minimum tensile adhesion strength of 0.08 N/mm^2 [28]. Depending on wind loads and insulation type, additional dowelling may be required. The type and number of dowels must be matched to the substrate, the insulation material and its thickness, building height, and various loads.

Traditional dowels feature a dowel pin or screw made of galvanized steel or stainless steel, and a dowel sleeve connected to the dowel plate, made of polyethylene or polyamide. It's important to differentiate between constructive and static dowelling: constructive dowelling serves as an assembly aid, supporting the system while the adhesive sets, while static dowelling is primarily used to transfer wind loads [28]. Various types of dowels are available depending on the application, including screw dowels, drop-in anchors, impact dowels, and drill dowels, with screw dowels being the versatile choice due to their wide application range [28].

The fixing method can accommodate varying degrees of substrate unevenness. For glued systems, the allowable deviation is up to one centimeter per meter. When using dowels, this value doubles to two centimeters per meter. The greatest deviation, three centimeters per meter, is permitted when using rail fixings [29].

The insulation itself, either EPS or XPS, is chosen for its thermal properties but presents challenges due to the presence of blowing agents and flame retardants, which can affect recyclability. EPS, commonly used, falls under fire behavior class B (flammable) [30] and may contain fire barriers to meet safety regulations. XPS, with its closed-cell structure, is often used in areas with high moisture levels due to its low water absorption.

The exterior side of the insulation is covered with an armoring layer of cement-based render reinforced with glass fiber or plastic mesh [31]. This layer protects the insulation, provides strength, and acts as a barrier. The final coat, typically a thin plaster layer, can be mineral or organically bound and may contain decorative elements.

The complexity and variety of these materials, combined with strong adhesion, present challenges in separating and recycling EPS and XPS waste from ETICS.

Current Practices in Demolition

The demolition of ETICS presents a significant hurdle in the recycling of EPS and XPS waste. Two primary methods are currently used, each with its own limitations in terms of material recovery and environmental impact:

- Conventional demolition: This method involves the complete removal of the ETICS, typically using mechanical means [32]. This results in a mixed waste stream of adhesive, insulation, mortar, mesh, and other components, making separation for recycling difficult and costly. This mixed waste is often landfilled or incinerated, leading to a loss of potentially valuable materials. While incineration can address the concern of HBCD, a hazardous flame retardant found in some EPS and XPS products [33], it is not a sustainable solution for resource recovery.
- Selective demolition: This approach aims to separate the ETICS components during demolition, either manually or through semi-selective mechanical methods [26]. Manual separation involves using hand tools to carefully detach the insulation from the other layers, allowing for better material recovery but is labor-intensive and time-consuming [26]. Semi-selective mechanical methods,

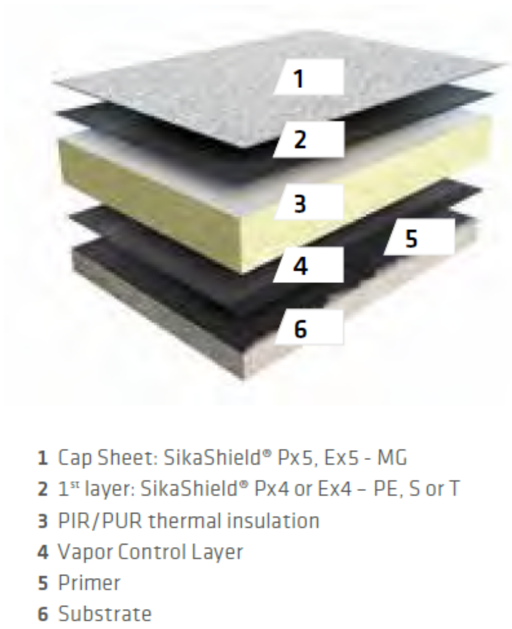


Figure 2.6: Bitumen layering [37]

like peeling off ETICS with an excavator, are faster but often leave residues on the facade, necessitating further cleaning or disposal.

The lack of specific legal guidelines in Austria for the demolition and disposal of ETICS further exacerbates the challenge. While clean separation of components aligns with the principles of the circular economy, there are no defined limits for contamination of mineral substances by thermal insulation, leading to inconsistencies in waste management practices [34].

Despite the potential value of recovered EPS and XPS, the current state of ETICS demolition often results in their disposal in incineration plants due to the complexities and costs associated with separation [26]. To improve the recycling rate of these materials, advancements in fully mechanical selective demolition techniques are needed. These technologies could enable efficient separation of ETICS components, increasing the recovery of valuable materials and reducing the amount of mixed waste destined for disposal. Additionally, establishing clear guidelines and regulations for ETICS demolition could incentivize more sustainable practices and promote a circular approach to construction waste management.

2.3.4. EPS from Roof Demolition - Contaminated with Bitumen

Bituminous membranes are often integrated to the construction and renovation of flat and sloped roofs in Austria, providing a robust, weather-resistant barrier. These membranes achieve a completely watertight surface, ensuring 100% protection against various weather conditions like heavy rain and hail. The bituminous sheets, typically composed of a carrier layer coated on both sides with bitumen, are favored for their elasticity and flexibility, which prevent cracking under temperature changes and mechanical stress [35].

The installation techniques vary, including self-adhesive options suitable for heat-sensitive areas and torch-applied methods where direct heat can be used [36].

Layering structure of bituminous material

The layering of bituminous membranes involves a meticulously engineered assembly designed to provide maximum waterproofing, durability, and thermal performance. Here's a detailed breakdown of each component in the typical bituminous roofing system:

- Primer layer nr.5 in figure 2.6: The application begins with a primer, essential for enhancing the adhesion of the membrane to the substrate and sealing its porosity, ensuring a durable and secure installation [38].

- Vapor control layer (VCL) nr.4 in figure 2.6: Positioned directly above the primed surface, this layer is critical for managing moisture by preventing the upward migration of water vapor, thus protecting the insulation and the interior of the building from moisture-related damage [38].
- Thermal insulation layer nr.3 in figure 2.6: Typically made from materials such as expanded polystyrene (EPS) or extruded polystyrene (XPS), this layer provides thermal resistance, contributing significantly to the building's energy efficiency. It is installed directly beneath the bituminous membranes [35].
- Bituminous membrane layers:
  - Base layer or underlay nr.2 in figure 2.6: The first bituminous layer applied over the insulation, which may be self-adhesive or torch-applied, depending on the installation requirements. This layer often contains modifiers to enhance the bitumen's flexibility and temperature tolerance. Additionally more layers of bitumen could be applied [38].
  - Cap sheet or top layer nr.1 in figure 2.6: This is the topmost layer, surfaced with materials like mineral granules to protect against UV rays and physical damage. It is important for the primary waterproofing, offering robust protection against environmental elements [38].
  - Protective finishes: Additional protective finishes such as gravel ballast or a green roof system may be applied to enhance the roof's protective qualities and aesthetic value. These finishes provide extra durability and can be tailored to specific environmental or usage requirements [38].
  - Detailing and flashing: Special attention is given to detailing and flashing around roof penetrations, edges, and terminations to ensure complete waterproofing. These areas are reinforced with additional bituminous materials or compatible sealing products to prevent leaks [38].

The correct assembly of these layers results in a durable, energy-efficient, and highly effective waterproofing system that can last for decades with proper maintenance. This multi-layered approach allows bituminous membranes to be a versatile solution adaptable to various architectural and climatic conditions.

2.4. EPS Waste Applications

This section explores innovative uses for EPS and XPS as construction waste after their use as insulation material. Beyond their traditional role as insulation this describes what literature proposes as waste applications for this material. By repurposing EPS and XPS waste materials, these versatile plastics can be integrated into various applications, reducing the need for incineration and promoting resource efficiency. Specific examples of how EPS and XPS waste can be incorporated into other materials will be examined, extending their lifespan and minimizing virgin material. However, the difficulty of separating EPS and XPS from other materials once they have been combined poses a significant challenge to recycling efforts and can limit the long-term environmental benefits of these applications due to dissolution. Despite this limitation, this section primarily focuses on the potential for downcycling these materials within the construction industry.

EPS has generated significant attention in the construction industry for its potential to be reused and revolutionize building materials. EPS's lightweight and insulative properties make it a favorable addition to concrete, creating innovative solutions that offer both environmental benefits and effective waste management [39], [40]. As well as this material can enhance asphalt for road construction [5].

2.4.1. Use of EPS in Concrete

EPS concrete is created by integrating EPS beads with traditional concrete components such as cement, sand and water. This mix typically replaces part of the aggregate with EPS, significantly reducing the weight and improving the thermal insulation properties of the concrete [41], [42]. Innovations like incorporating rice husk ash alongside EPS in lightweight concrete bricks highlight the industry's move towards sustainability [40].

Recent studies have explored further advancements in EPS utilization for concrete production, including the use of recycled EPS to enhance environmental sustainability. Research has demonstrated that incorporating mechanically recycled EPS can effectively reduce the density of concrete without compromising its structural integrity, thus promoting greener construction practices [43], [44].

Specific Applications

EPS concrete is utilized across several construction scenarios:

- Lightweight blocks and panels: These materials are used for building non-load-bearing walls, significantly easing installation and reducing structural loads [41], [39].
- Thermal and acoustic insulation: Due to its excellent insulation properties, EPS concrete is ideal for floors and roofing, enhancing a building's energy efficiency [40].
- Infrastructure void filling: In roads and bridges, EPS concrete reduces dead load, maintaining structural integrity with less weight [41].
- Decorative elements: EPS's versatility allows for the creation of intricate shapes and designs that are impractical with heavier materials [39].

Further applications include the use of EPS as an ultra-lightweight aggregate in structural elements, offering potential improvements in mechanical properties such as compressive strength and flexural rigidity, particularly in specialized constructions like sandwich wall panels for lightweight structures [45].

Environmental Benefits and Challenges

Incorporating recovered expanded polysterene (EPS) into concrete offers a dual-edged approach to environmental sustainability. Utilizing EPS diverts significant amounts of non-biodegradable waste from incineration, aligning with sustainable construction practices and reducing the overall environmental footprint. This process not only minimizes waste but also leverages the lightweight and insulative properties of EPS to enhance building efficiency [41], [40]. However, the environmental benefits are tempered by the challenges associated with EPS's lifecycle. As a downcycled material, EPS does not biodegrade, potentially leading to long-term environmental pollution if not properly managed. Moreover, incorporating EPS into concrete can complicate end-of-life recycling processes for both materials, as separating the plastic from the concrete matrix becomes very challenging and costly [41], [40].

Moreover, the use of recycled EPS, sourced predominantly from post-consumer waste, adds further complexity. It requires meticulous separation and cleaning processes to ensure that these materials are reintegrated into concrete production without contaminants, which could compromise structural integrity [43], [44]. Additionally, the energy and resource consumption involved in the recycling process might negate some of the environmental savings achieved through its use in concrete, given that the production of EPS itself is an energy-intensive process that contributes to air quality degradation and carbon emissions [45].

Further complicating the environmental assessment, integrating EPS along with other waste materials like rice husk ash into concrete formulations can reduce the cement content significantly, thus lowering CO_2 emissions associated with cement production [40]. However, these benefits must be carefully weighed against the full lifecycle impacts of such practices—from raw material extraction through to end-of-life disposal or recycling—to ensure that they deliver genuine sustainability gains. The integration of waste materials in construction demands meticulous evaluation to ascertain that the environmental advantages are not overshadowed by unintended ecological consequences [40], [41].

Technical and Long-term Considerations

EPS concrete generally exhibits lower compressive strength compared to traditional concrete, restricting its use to non-structural applications unless reinforced [41], [39]. Concerns about its water absorption and long-term durability could be compromised due to the hydrophobic nature of EPS [40], [42].

Innovative approaches are being explored to enhance the performance of EPS-based concrete through the use of additional modifiers like silica fume and superplasticizers, which have shown promising results in improving the material's strength and durability, thus expanding its applicability in more demanding structural roles [46].

The integration of EPS in concrete does not fully address the lifecycle of the material. Since EPS does not biodegrade, its incorporation into concrete must be carefully considered to avoid future environmental burdens [40], [47]. Future research should focus on enhancing the material's structural properties and developing sustainable alternatives to EPS that maintain its beneficial characteristics without the associated environmental costs [42].

EPS concrete stands out as an innovative material that offers reduced weight, improved insulation, and utilization of waste materials. However, its use in construction must be strategically managed to maximize benefits while minimizing potential long-term environmental impacts. Future research should focus on enhancing the material's structural properties and developing sustainable alternatives to EPS that maintain its beneficial characteristics without the associated environmental costs [47], [42].

2.4.2. Use of of EPS in Asphalt Modification

EPS is recognized for its utility beyond packaging and insulation, notably in enhancing asphalt for road construction. This lightweight, insulative material addresses critical environmental and infrastructural needs by being repurposed in asphalt modifications. Its ability to remain stable and functional at temperatures above 100°C makes it particularly suited for integration into asphalt, which frequently operates under such thermal conditions, thus providing resilience against temperature-induced degradation [5].

The integration of EPS into asphalt follows a sophisticated methodological framework, ensuring the transformed material contributes effectively to asphalt properties. The process begins with the dissolution of EPS waste in a solvent mixture, typically acetone and ethyl acetate, to achieve a specific viscosity. This adhesive material, once prepared, is pivotal in modifying asphalt by enhancing its binding properties or as a protective coating, impacting overall pavement performance [48].

During the asphalt production phase, the prepared EPS mixture is introduced at critical points based on desired outcomes:

- Binder enhancement: EPS is mixed directly with bitumen to enhance the binder's adhesive properties, improving the overall cohesion within the asphalt.
- Surface coating: For surface applications, EPS is either applied directly to the aggregate or sprayed onto the completed pavement, providing additional protection and durability.

Temperature management is important throughout the EPS incorporation process, ensuring that the solvent evaporates completely without compromising the structural integrity of both the EPS and the asphalt mix. This step is followed by a thorough homogenization process, where the mixture is mechanically stirred to distribute the EPS evenly, avoiding any potential clustering that could affect the pavement's performance.

Post-application, the asphalt containing EPS requires controlled curing to facilitate the complete development of its adhesive and cohesive properties. This curing process is critical, requiring precise management of environmental conditions such as temperature and humidity to ensure the material cures without any detrimental effects, thereby optimizing the asphalt's performance characteristics in the finished pavement.

Studies investigating the inclusion of shredded EPS in asphalt concrete, such as those by Akter et al [49], demonstrate significant enhancements in asphalt's physical properties. Notably, a mere 0.5% addition of EPS by weight of the total aggregate optimizes the mixture, significantly increasing its stiffness and resistance to deformation. This optimal concentration leads to an 82.61% improvement in stability compared to conventional asphalt mixes, underscoring EPS's role in enhancing load-bearing capacity and durability of road surfaces [49].

Environmental Impact and Sustainability Benefits

Incorporating EPS into asphalt goes beyond improving material properties; it offers a sustainable approach to managing EPS waste. This practice helps reduce the reliance on virgin bitumen, conserves natural resources, and diminishes the environmental footprint of road construction, aligning with global efforts towards sustainability [49]. Though this can be seen as a environmental friendly solution it also poses questions about the end of life scenario of the EPS asphalt after its use as separation of these materials will not easily be possible

Further validation through SEM and XRD techniques confirms that EPS is compatible with asphalt mixtures, not altering the crystalline structure of asphalt and thus maintaining the pavement's stability under varying temperatures. Moreover, thermal analysis like differential scanning calorimetry and thermogravimetric analysis highlight EPS's ability to withstand different climatic conditions, ensuring the modified asphalt remains durable over time [50].

The integration of EPS into asphalt represents a significant advancement in materials technology for road construction, promising enhanced durability and environmental sustainability. The ongoing research and development are important for optimizing the integration processes and fully realizing the long-term benefits of EPS-modified asphalt in various environmental conditions.

2.5. Recycling Technologies for EPS and XPS

The escalating use of EPS and XPS in various industries has brought significant environmental challenges due to their resistance to natural degradation and bulky nature [51]. These polystyrene materials, popular for their insulating properties and lightweight characteristics, contribute heavily to plastic waste accumulation and pose significant disposal issues [52]. Recognizing the urgency to mitigate the environmental footprint of EPS and XPS, this review looks into the current practices of recycling and reusing these materials, focusing on existing technologies and their suitability for different polystyrene waste streams. Current recycling methodologies for EPS and XPS encompass a combination of mechanical and feedstock/chemical recycling processes, both requiring initial volume reduction through compaction or densification [51]. This step addresses the low-density issue and prepares the material for subsequent processing.

As illustrated in figure 2.7, mechanical recycling involves the breakdown of polystyrene waste into smaller pieces. These fragments undergo a series of steps including cleaning, drying, and ultimately, remolding into new products [51]. This method is advantageous due to its simplicity and adaptability to various polystyrene types [53].

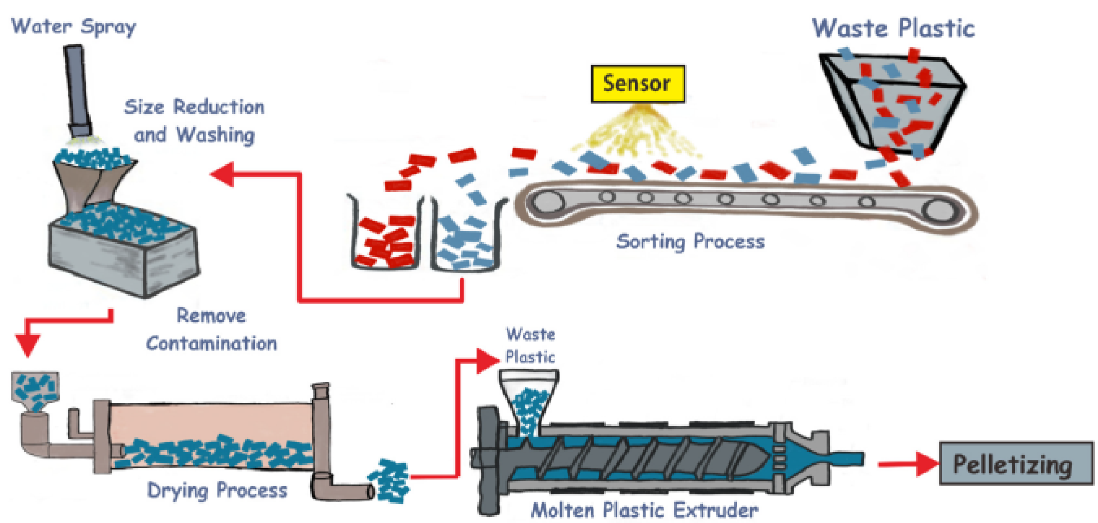


Figure 2.7: Mechanical recycling [51];
The blue parts are indicating the PS waste,
the red parts are indicating the contamination.

The mechanical recycling process begins with the size reduction of waste plastic through shredding or cutting [54]. Following this, the plastic undergoes a washing process to remove contaminants and impurities. The cleaned plastic is then dried thoroughly. Finally, the dried plastic is melted and extruded into pellets, ready for reuse in manufacturing new products [55].

EPS is effectively recycled through mechanical processes. However, its low density often necessitates densification prior to reprocessing, and contamination from additives or other materials presents significant challenges for this recycling method. In contrast, XPS presents greater challenges in mechanical recycling due to its higher density and rigid structure, necessitating more energy and specialized equipment for processing [53], [56].

Chemical recycling techniques offer an alternative approach, particularly for contaminated or mixed material streams. Processes like dissolution significantly reduce EPS and XPS volume, facilitating the removal of impurities [51]. Additionally, pyrolysis and catalytic degradation techniques enable the conversion of these materials into valuable chemical compounds even without extensive pre-treatment.

For EPS, chemical recycling methods such as dissolution in limonene and other environmentally friendly solvents are promising, especially for removing contaminants and achieving closed-loop recycling. Additionally, processes like pyrolysis and catalytic degradation are effective in converting EPS into valuable chemicals or fuels. XPS, on the other hand, is well-suited for pyrolysis and catalytic degradation, allowing it to be broken down into valuable monomers and other chemical feedstocks [57], [56].

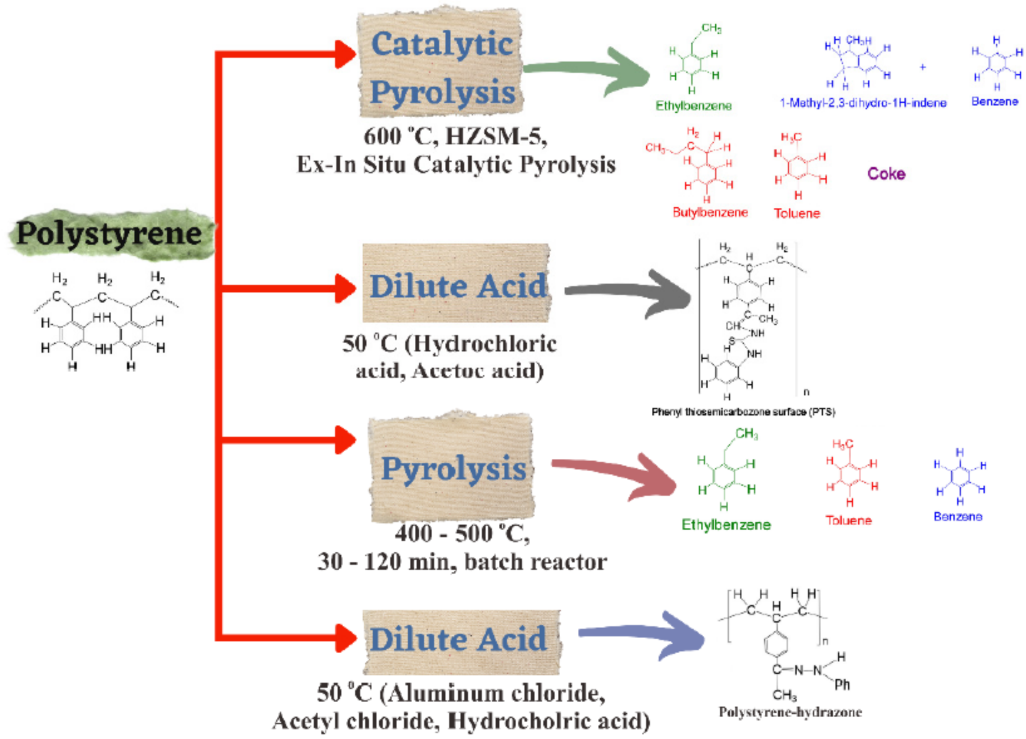


Figure 2.8: PS degradation [51]

Figure 2.8 showcases the diverse pathways for PS degradation through chemical recycling [58]. Catalytic pyrolysis, employing a catalyst at high temperatures, yields valuable products like ethylbenzene, toluene, and benzene. Dilute acid treatments using hydrochloric acid or acetic acid lead to the formation of poly(styrene-co-hydrazone). Pyrolysis without a catalyst also results in the breakdown of PS into ethylbenzene and toluene.

Thermal methods, such as microwave-assisted pyrolysis, are particularly effective for EPS and XPS due to their ability to rapidly heat and decompose large volumes of polystyrene waste into usable products [59].

Microwave-assisted pyrolysis is particularly suited for EPS due to its ability to efficiently heat and decompose the material, making it a favorable option for managing large-volume EPS waste. For XPS, while thermal methods like microwave-assisted pyrolysis can be applied, its higher density may require longer processing times or higher energy input compared to EPS [59].

The choice of recycling method depends on the specific type of polystyrene waste. For EPS, which tends to be bulky and potentially contaminated with construction residues, techniques like dissolution and microwave-assisted pyrolysis are preferred [51]. These methods effectively address the material's volume and allow for the separation of EPS from other materials [60]. In contrast, XPS, with its denser and more rigid structure, is well-suited to chemical recycling processes like pyrolysis and catalytic degradation [53]. These processes enable the efficient separation and conversion of XPS into monomers or other valuable substances.

Effective separation of plastic waste is important for successful recycling. Technologies such as optical sorting, density separation, and flotation are essential for separating different types of plastics before the recycling process [60], [54].

Despite advancements in recycling technologies, achieving high-quality 'closed-loop' recycling for EPS and XPS remains a challenge [61]. Research has highlighted the difficulties in material recycling through melting, indicating the need for continuous innovation and development of technologies that can effectively close the loop on polystyrene waste [57].

The primary distinction in recycling technology for EPS and XPS lies in their density. EPS, with its lower density, benefits from volume reduction techniques such as dissolution before further processing. In contrast, the denser XPS is more suitable to the direct application of chemical or thermal methods. The presence of flame retardants or other additives in XPS can complicate certain recycling methods, needing specific pre-treatment steps to remove these additives before recycling can proceed effectively. Both EPS and XPS can be contaminated with other materials depending on their application, making effective sorting and separation techniques important for ensuring the quality of recycled polystyrene.

Feature	EPS	XPS
Mechanical recycling	- *Processes:* Grinding, re-granulation - *Needs:* Densification for low density - *Challenges:* Contamination and additives	- *More challenging* due to density and rigidity - *Requires:* More energy, specialized equipment
Chemical recycling	- *Methods:* Dissolution in limonene, pyrolysis, catalytic degradation - *Benefits:* Contaminant removal, closed-loop recycling	- *Methods:* Pyrolysis, catalytic degradation - *Products:* Valuable monomers, chemical feedstocks
Thermal recycling	- *Method:* Microwave-assisted pyrolysis - *Suited for:* Large-volume waste	- *Consideration:* Higher energy input due to density
Density considerations	- *Benefit:* Suitable for volume reduction techniques	- *Direct methods:* Chemical or thermal recycling more effective
Additive challenges	- *Need:* Treatment for additives or contaminants	- *Challenges:* Flame retardants, pre-treatment needed
Contamination issues	- *Sorting:* Effective techniques required	- *Sorting:* Important for quality recycling

Table 2.3: Comparison of EPS and XPS recycling

3

EPS and XPS Market in Practice

This chapter provides an overview of the current EPS and XPS market, encompassing production methods, recycling initiatives, waste management practices, and the practical implications of these materials in construction. It explores the current state of the EPS and XPS market, examining the roles of various stakeholders and exploring the complexities of recycling these materials. It utilizes interviews, site visits, and detailed analysis to highlight both challenges and innovations within the industry, offering a comparative analysis of approaches in Austria and the Netherlands.

3.1. Market Overview: Suppliers, Consultants and Initiatives

The EPS and XPS market involves a wide range of stakeholders, each playing a crucial role in the production, utilization, and recycling of these materials. Understanding their perspectives and practices is essential to assess the current state of the market and identify potential areas for improvement.

3.1.1. Insulation Producer - Austrotherm (Austria)

Austrotherm provided significant insights into their strategies and challenges regarding the production and recycling of XPS and EPS insulation panels. The aim is to understand how a leading producer addresses sustainability in their operations, particularly in the context of recycling. Austrotherm emphasized their integral role in collecting uncontaminated EPS and XPS waste from construction sites, aiming for a recycling rate of approximately 70%.

During the talk, it was revealed that the majority of XPS's production-related CO_2 emissions stem from raw material usage which also makes recycling material more attractive. The disposal cost for EPS, currently estimated at €400 per ton, reflects a collaborative effort among various industry players to manage waste efficiently. However, this cost can surge to as much as €3000 per ton for materials contaminated with hazardous substances like HBCD necessitating incineration.

Austrotherm's recycling process for XPS includes shredding the material into 2cm flakes, which are then extruded into granules and reintroduced into the production cycle. This granulate can replace a portion of the raw materials, contributing to a circular economy. For EPS waste from construction sites, the level of contamination dictates the treatment approach. Low-contamination EPS is often recycled without preliminary treatment, while more contaminated materials may require complex processing or even downcycling, such as use in lightweight concrete applications.

Furthermore, Austrotherm is part of a consortium that manages EPS recycling, with several pickup points across Austria. In chapter **??** the different options for the construction company FREY will be discuss. The mechanical recycling process at Austrotherm involves a series of steps where EPS is broken down, contaminants are separated, and the material is ultimately reintroduced into production, achieving about 4% material reintegration from their sales.

The logistical challenges of recycling EPS are intensified by its low density, which makes transportation less economical due to the need for far travel. This also limits the amount of material being recycled.

To mitigate this, Austrotherm is developing a pickup service designed to operate within a 200km radius, aiming to improve the efficiency of EPS recycling logistics.

This discussion with Austrotherm not only highlighted the intricate details of their recycling practices but also underscored the broader industry dynamics and their proactive approach to enhancing sustainability in building materials through advanced recycling technologies and collaboration.

3.1.2. Collaborative Project - Frauenhofer - EPSolutly (Austria/Netherlands)

The EPSolutly initiative, managed by the Frauenhofer Institute in Vienna, represents a major collaborative endeavor focusing on the sustainable lifecycle of EPS materials. As one of the largest initiatives of its kind, it brings together a broad coalition of more than 15 stakeholders from various sectors—including EPS producers, pre-consumer processors, transportation companies, construction and demolition firms, and waste management and recycling entities across Austria. The project's goal is to improve the recycling rates of EPS and to address the challenges hindering its broader recovery, as approximately 690 kt of EPS were present on Austrian facades in 2016 [62].

From two representatives of Frauenhofer Institute, further details were revealed about the initiative's structure, which includes three focused phases: packaging, construction sites, and demolition. The construction site phase specifically targets the recycling of unused EPS cutoffs, which constitute about 6% of the materials delivered on site. These materials, having never been mixed with other substances, are collected and directly recycled by the producers. The demolition phase tackles more complex challenges, as it deals with EPS that is attached to various other construction materials such as plaster and glue. The efforts in this phase are concentrated on refining demolition and transportation processes to optimize recycling practices. This work does not cover the packaging phase within this scope, as it primarily concentrates on the construction industry's needs and challenges. This approach reflects on the strategic insights from the project management on the potential solutions to extend the use of EPS beyond its initial lifecycle, thus underlining the critical importance of this environmental issue.

Construction Site

An innovative system implemented by Frauenhofer Austria for the collection, recycling, and tracking of EPS waste at construction sites, further showcasing the commitment to sustainability and resource efficiency in the building industry.

The process begins with the provision of specially marked bags equipped with QR codes and RFID (radio frequency identification) tags to collect EPS offcuts at the construction site. Approximately 7% of EPS used on-site ends up as offcuts, which are typically considered waste. By providing these bags, the goal is to facilitate an organized collection and ensure that these materials do not end up in landfills or incineration.

The collection process is supported by a digital infrastructure that includes an app, enabling efficient scheduling and coordination of EPS waste pickup. This system leverages QR code scanning for easy tracking and processing of the collected material. The tracking mechanism is further enhanced by RFID technology, which allows for detailed data collection and monitoring throughout the recycling process. Automated workflows ensure that the entire process, from collection to recycling, is streamlined and efficient.

The collected EPS waste is then taken to a recycling facility, following a well-structured and efficient network for collection and back-transport, as depicted on the zone maps. These visual aids illustrate the radius within which the collection hubs are set up and the direct transportation routes to the EPS processing plant.

Once the material reaches the recycling facility, it undergoes a cleaning process to ensure it's free from contaminants. The EPS is granulated into individual beads, with the separation of dust and other impurities enhancing the quality of the recycled product. State-of-the-art machinery is used for both granulation and cleaning, with an emphasis on achieving high-quality recyclable EPS beads that are almost identical akin to new material in terms of their properties.

These recycled EPS beads are then utilized to produce new EPS blocks and panels with varying proportions of recycled material, demonstrating the practical application of the recycled EPS in the production of new construction materials.

Demolition

The EPS recycling procedure after demolition begins with the careful deconstruction of insulation systems, where machinery equipped with specialized attachments strip EPS panels from building exteriors. Once these materials are removed, they're gathered and subjected to a size reduction phase. During this phase, EPS is manually or mechanically broken down, isolating it from other substances such as adhesives or plaster.

After the collection and downsizing using the shredder "Lindner Recyclingtech" Model: Antares 1600 to downsize the material, the EPS material is sorted using the separator IFE Sort. Through a precision process leveraging vibration and airflow, efficiently separating lighter EPS particles from heavier, non-EPS materials. The subsequent compaction phase significantly reduces the material's volume, thus streamlining transportation logistics to the recycling facility.

Upon arrival at the recycling site, the compacted EPS undergoes a dissolution and purification process. It is immersed in a solvent, facilitating the detachment of EPS from any residual contaminants. The clean EPS is then subjected to a series of purification steps — filtration, precipitation, and distillation — culminating in the extraction of pure polystyrene, the fundamental component of EPS.

The problem of this recycling is the transformation of this purified polystyrene into a PS recyclate. This new form of polystyrene can be repurposed to produce various products, completing the lifecycle of the material and embodying the principles of a circular economy.

3.1.3. Sustainability Consultancies - EPEA (Austria)

The interview with the leading sustainability consultancy EPEA in Austria provided in-depth insights into their perspective on the challenges and solutions related to recycling EPS and XPS within the construction industry. The consultancy expressed concerns over the economic and logistical hurdles of post-consumer recycling for these materials, highlighting that while pre-consumer recycling is economically viable, post-consumer practices are hindered by high costs and logistical complexities. They noted that the only viable method for recycling EPS and XPS post-consumption, known as CreaSolv®, is not cost-effective and requires transporting waste to the Netherlands, where the only operational facility exists.

The consultancy pointed out that EPS and XPS materials in existing buildings are rarely recycled post-manufacture due to the costs exceeding the material value and high contamination levels. They mentioned innovative systems, such as the Weber Therm Circ developed by WEBER SAINT GOBAIN [63], which facilitates the layer-by-layer deconstruction of thermal insulation composite systems, making recycling more feasible. This system will be further touched in chapter 5. However, they criticized the high costs and limited adoption of such systems.

On the topic of materials, the consultancy strongly advocated for alternative insulation materials like mineral wool, which includes glass wool and stone wool, despite potential health risks. They praised the efforts of rockwool, a manufacturer that actively samples materials on construction sites to repurpose them, demonstrating the practical recyclability of mineral wool.

The consultancy also emphasized the significant challenge of contamination in recycling EPS and XPS. They advocate for minimizing the use of fossil-based insulation materials in new constructions, suggesting alternatives such as mineral wool for fire protection, expanded glass for floor slabs, wood fiber for sound insulation, and cellulose. They argued that while EPS is economically attractive, materials like crushed glass, though more costly, offer superior recyclability and are preferable for long-term sustainability.

The consultancy, is actively working to shift industry standards towards sustainable practices. They are involved in collaborations with architects and the construction industry to promote the reuse of building components, which supports the deconstruction and repurposing of materials while maintaining product warranty and quality.

Overall, the consultancy's points are clear clear: they are pushing for a transition to more sustainable, recyclable materials in the construction industry, and they are engaging with industrial partners to incorporate these practices into a circular economy model. Their advocacy for solutions like Weber

Therm Circ [63], which promote the purity and recyclability of construction materials, underscores their commitment to environmental sustainability and economic viability in recycling practices.

3.1.4. Research Center - (Netherlands)

The head of plastics recycling research in the Netherlands mentioned that there was currently no research ongoing in the recycling of plastic construction waste as the problem of recycling of normal plastic waste is still a bigger topic for them and has been since 25 years but has not been fixed yet. This is why they are still researching to get better at recycling for ”conventional” waste and there is currently no research on plastic waste in the construction sector.

3.1.5. Conclusion

In both Austria and the Netherlands, the EPS and XPS market is characterized by a growing emphasis on sustainability and recycling. However, the approaches differ. In Austria, there’s a strong focus on collaborative initiatives like EPSolutly, involving various stakeholders across the EPS lifecycle. The Netherlands, while also concerned with sustainability, is currently prioritizing research on ”conventional” plastic waste over construction-specific plastics. This highlights a potential area for growth in the Dutch market.

3.2. EPS and XPS in Construction Practice

To understand the practical implications of EPS and XPS, it’s essential to examine their real-world use and the unique challenges faced in different regions. This section explores the material properties, application diversity, waste management practices, and economic considerations surrounding EPS and XPS in Austria and the Netherlands, providing a comparative analysis to highlight both commonalities and regional differences.

3.2.1. Material Properties

The selection of insulation materials like EPS and XPS is a critical decision for architects, engineers, and construction companies due to their distinct properties influenced by unique manufacturing processes. Each material suits different construction applications, impacting building performance, durability, and energy efficiency. Understanding these differences enables professionals to optimize the use of materials in projects.

EPS, composed of individual beads fused together, is known for its versatility and cost-effectiveness. It strikes a balance between thermal performance and affordability, making it a popular choice for diverse applications:

- **Wall insulation:** EPS is integral in Structural Insulated Panels (SIPs) and Insulated Concrete Forms (ICFs), enhancing energy efficiency in buildings
- **Roofing systems:** The lightweight nature of EPS suits green roofing systems, supporting vegetation without adding excessive weight
- **Floor insulation:** Employed beneath concrete slabs and in retrofit projects, EPS improves thermal insulation
- **Geotechnical applications:** Used as lightweight fill in road embankments and behind retaining walls, EPS helps manage ground pressure and settlement

On the other hand, XPS, with its uniform, closed-cell structure, boasts superior compressive strength and moisture resistance compared to EPS. This makes it a preferred material for applications where these properties are paramount:

- **Below-grade insulation:** XPS in foundation walls, basements, and slabs, providing critical water resistance and insulation
- **Perimeter insulation:** In buildings, XPS is used to prevent thermal bridging and protect against moisture around the foundation
- **Cavity wall insulation:** The rigidity and moisture resistance of XPS ensure sustained thermal performance

- **Inverted roof insulation:** Suitable for flat roofs, XPS withstands elements and supports maintenance activities

Impact of Manufacturing on Construction Applications

The distinct manufacturing processes of EPS and XPS significantly influence their structural properties and application suitability. EPS is manufactured in a way that allows for a range of densities, from lightweight forms to dense, durable panels, catering to diverse construction needs. Conversely, XPS is produced through continuous extrusion, resulting in a dense, homogeneous material with enhanced moisture resistance and compressive strength. This makes it ideal for high-load applications or environments with substantial moisture exposure.

These manufacturing distinctions play an important role in determining the appropriate material for specific construction projects. The table 3.1 below summarizes the key differences between EPS and XPS.

Type	**EPS (Expanded Polystyrene)**	**XPS (Extruded Polystyrene)**
Structure	Beads fused together, lighter	Uniform, closed-cell, denser
Moisture resistance	Lower	Higher
Compressive strength	Lower	Higher
Typical uses	Wall, floor, and roof insulation, geotechnical applications	Below-grade, perimeter, and cavity wall insulation, inverted roofs

Table 3.1: EPS vs. XPS in construction applications

3.2.2. Construction Company - FREY (Austria)

In Austria, the use of EPS and XPS is widespread in various construction applications, as detailed in the section above. However, the end-of-life management of these materials, particularly during demolition, poses significant challenges. FREY's practices highlights the complexities of separating and processing EPS and XPS waste.

Material separation is crucial during demolition, especially when dealing with different materials bonded together. FREY employs a combination of manual and mechanical techniques to address this challenge. Manual separation is often preferred for smaller quantities or easily detachable layers, such as those found in floor slabs or non-adhered roof insulation. However, for more complex situations where materials are firmly bonded with adhesives or mortar, mechanical methods are essential. The company utilizes small machines and excavators equipped with specialized attachments to facilitate separation. Technological advancements, like specialized stripping machines designed to handle particularly tough adhesives, have emerged to enhance the efficiency of this process.

Despite these efforts, separating materials that are glued together remains a significant hurdle. Achieving complete separation is often impossible, and for economic reasons, the focus often shifts to recovering heavier materials like concrete and bricks, which have higher recycling value. The labor-intensive task of separating glue from insulation materials is frequently overlooked due to the prohibitive cost.

To optimize recycling and cost-efficiency, FREY collects EPS and XPS separately, typically storing them in large bags or metal containers depending on the volume. Materials contaminated with adhesives are also segregated. Additionally, during construction, smaller offcuts of insulation materials are promptly removed from the site and stored separately to prevent contamination, thereby enhancing the purity and recyclability of the collected materials.

The effectiveness of these separation practices has a direct impact on the overall recycling rate and associated costs. Pure, uncontaminated materials incur lower disposal fees at waste management facilities. In 2023, FREY delivered 1.4 tonnes of XPS and 0.42 tonnes of EPS to a waste management company, which charged significantly different rates for each material due to their purity and ease of processing – €5,100 per tonne for XPS and €600 per tonne for EPS. This economic disparity underscores the importance of implementing effective separation and recycling strategies in construction waste management.

The recycling sector in Austria is characterized by a diverse range of initiatives and an evolving market. Notably, the costs associated with waste incineration are relatively high, incentivizing the exploration of alternative waste management strategies. However, the problem faced by FREY exemplifies a broader issue in the industry. The diverse waste streams generated by various EPS and XPS applications, coupled with varying levels of contamination, pose a significant barrier to implementing specialized recycling processes. As a result, many companies rely on waste management companies to handle their EPS and XPS waste, which in turn face regulatory hurdles and difficulties in identifying and separating materials, particularly those contaminated with flame retardants.

3.2.3. Current Practices in the Netherlands

In contrast to Austria's diverse construction practices, the Netherlands exhibits a distinct preference for cavity wall construction (figure 3.1). This construction method significantly influences the choice of insulation materials and the subsequent challenges in waste management.

Figure 3.1: Cavity wall [64]

A key observation from field analysis in Delft is the extensive use of polyurethane alongside EPS, often as a substitute for XPS. This poses challenges in waste management, as polyurethane's visual similarity to XPS makes accurate identification difficult on construction sites, hindering effective separation and recycling efforts.

During site visits at Ternatestraat, Sabangstraat, and Julianalaan, a significant amount of unused EPS and polyurethane panels were observed being discarded along with other construction debris like concrete and bricks. This waste pattern highlights the need for improved waste management practices and material separation protocols at construction sites in the Netherlands.

To understand the integration of EPS and polyurethane in Dutch construction, a walkthrough of a typical cavity wall assembly was conducted. The layout as also demonstrated in figure 3.2 begins with an outer brick layer, followed by a 3cm gap, a layer of foil for water tightness, a timber structure interspersed with polyurethane or EPS panels, and finally, wooden and gypsum boards or as in Figure 3.2 suggested block work. This layering creates a comprehensive insulation system that underscores the importance of these materials in Dutch construction.

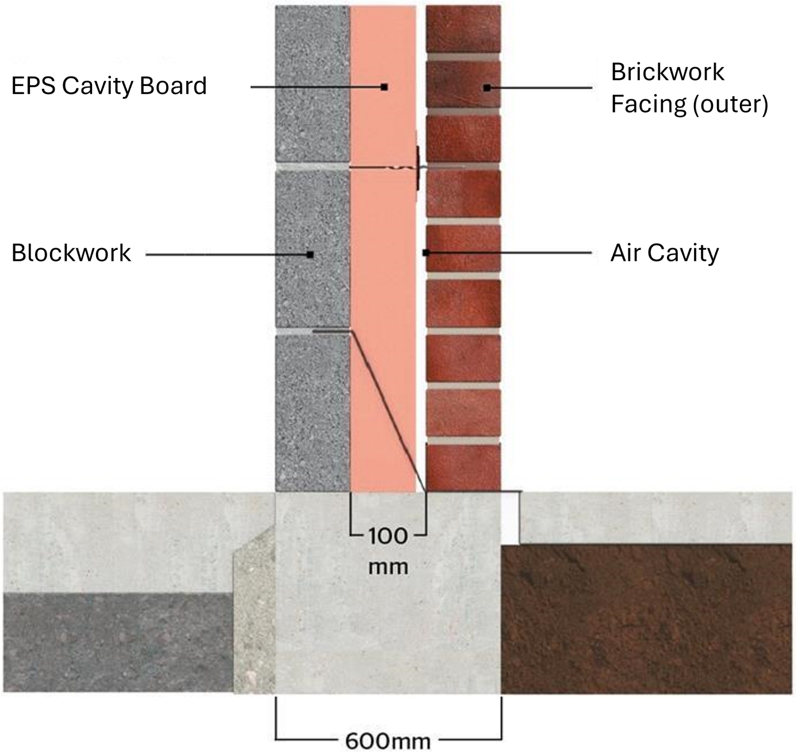


Figure 3.2: Demonstration of cavity structure [65]

3.2.4. Financial Implications

The financial aspects of EPS and XPS usage highlight a common concern in both Austria and the Netherlands: the need to balance initial construction costs with long-term disposal expenses. The Dutch experience mirrors the Austrian findings, where the cost of demolition and disposal can sometimes surpass the initial investment in materials.

This cost imbalance raises important questions about the sustainability of material choices in the construction industry. Stakeholders who invest in the initial construction may not be held accountable for the later disposal costs, leading to potential underinvestment in more sustainable or recyclable materials.

Furthermore, the prevalence of bonded materials, particularly in cavity wall constructions, complicates recycling efforts and adds to the overall cost burden. While downcycling EPS by shredding and mixing it with cement for flooring applications extends its lifespan, it merely delays the inevitable disposal problem and falls short of achieving a truly circular economy. This underscores the need for a shift towards materials that are not only cost-effective in the short term but also designed for easier separation and recycling in the long run.

3.2.5. Current Material Flow

The following flowcharts in figure 3.3 and figure 3.4 for Austria and the Netherlands illustrate the current trajectories of EPS and XPS within the waste management system. Despite some recycling and reuse initiatives, a substantial portion of EPS and XPS waste ends up in incineration. This emphasizes the ongoing need for innovation and collaboration across the industry to improve recycling rates and minimize the environmental impact of these materials.

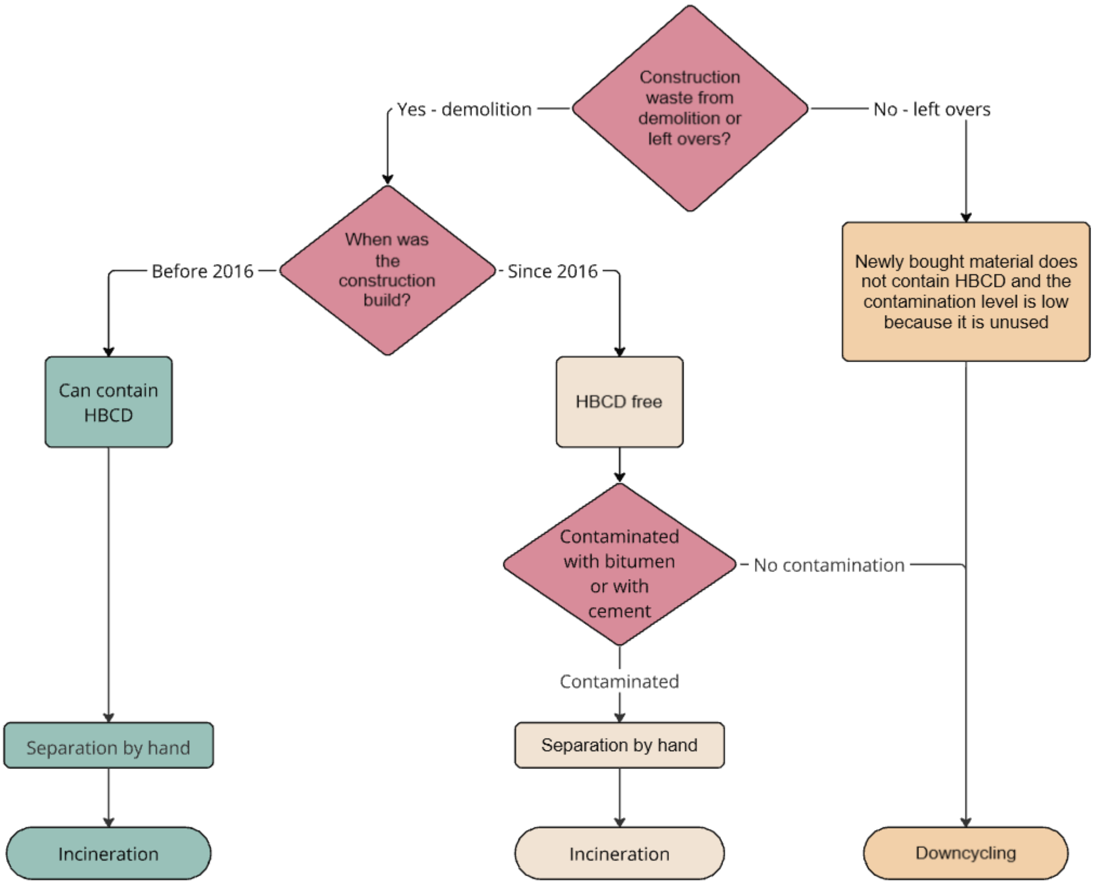


Figure 3.3: Current flowchart EPS

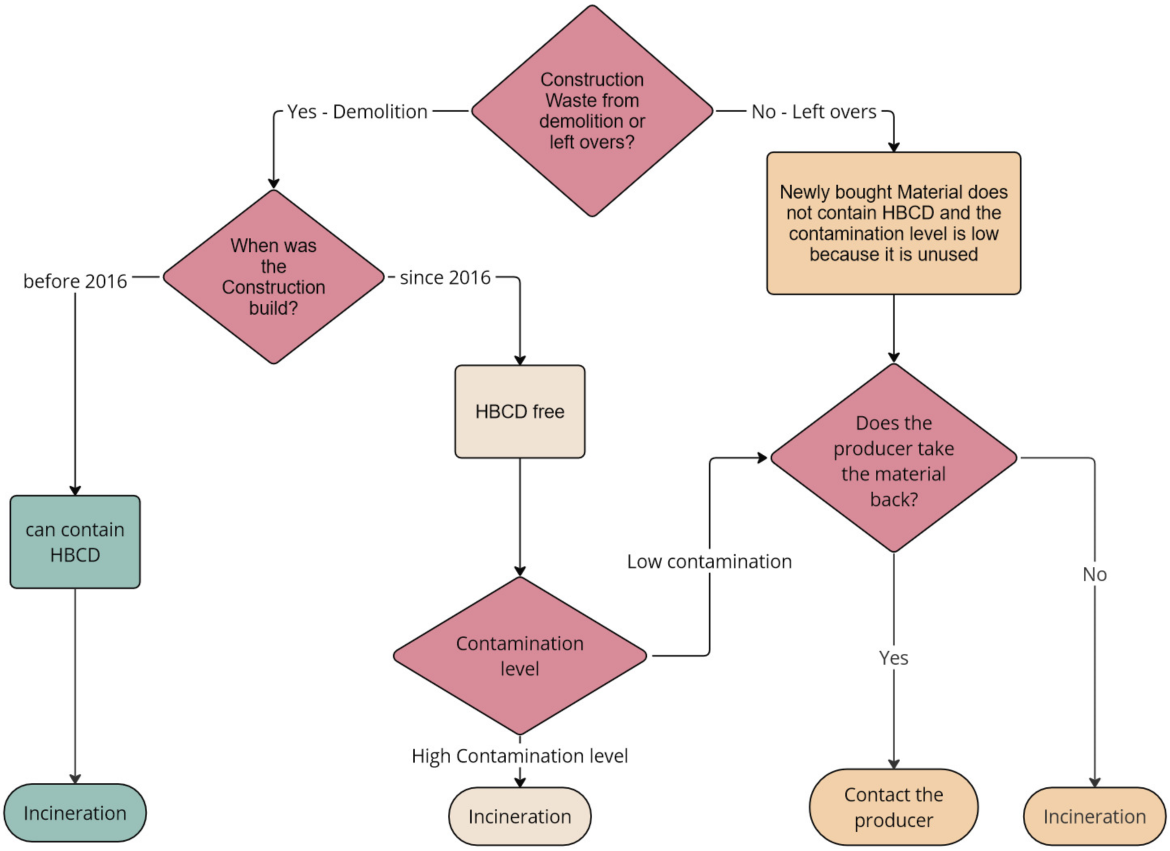


Figure 3.4: Current flowchart XPS

3.2.6. Conclusion

The comparative analysis reveals a complex EPS and XPS market, marked by both challenges and opportunities. While both Austria and the Netherlands are confronted with waste management and recycling hurdles, their distinct approaches offer valuable insights. Austria's focus on collaborative initiatives like EPSolutly and the Netherlands' embrace of innovative solvent-based recycling technologies like PS Loop's CreaSolv® process demonstrate the potential for positive change.

Looking ahead, addressing the economic barriers to recycling, refining separation techniques, and investing in the development of more easily recyclable materials will be crucial steps in minimizing the environmental footprint of EPS and XPS. By embracing a lifecycle perspective that considers both the initial cost and the long-term environmental impact of materials, stakeholders can make informed decisions that contribute to a more sustainable and circular construction industry.

3.3. Waste Management and Recycling

The waste management and recycling of EPS and XPS present significant challenges due to the materials' properties, contamination issues, and regulatory complexities. This section examines the practices of waste treatment companies, innovative recycling technologies, and the logistical considerations involved in managing EPS and XPS waste

3.3.1. Waste Treatment Company - Rossbacher (Austria)

The discussion with the waste management company provides a comprehensive look into the complexities of recycling EPS and XPS in Austria, highlighting the intricate processes and regulatory challenges involved in striving for a more sustainable and environmentally responsible waste management practice. An interview was conducted with this company, known for managing waste for FREY, which highlights the detailed procedures for sorting and recycling these materials, as well as the legal and environmental hurdles that complicate their processing.

The general process begins with the inspection of the contents within a dumpster. Based on the quantity of material — whether it's a small amount like 5kg or larger quantities up to 1 ton—the material is either manually or mechanically sorted. Smaller amounts typically proceed directly to landfill as bulky waste, whereas larger quantities are separated into recyclable and non-recyclable materials. Non-recyclables are then sent to waste-to-energy facilities, such as Simmeringer Haide, Vienna, Austria, for disposal.

Uncontaminated EPS undergoes shredding and is then sold to be reused and downcycled to a facility in Carinthia, for example, "Thermobound - EPS Leichtbeton". This process is also described in 2.4.1. However, a critical condition for reusing EPS is proof that the material does not contain any flammable substances or other substances that are not allowed to be further processed and must be separated. This requirement poses a significant challenge, as it's often unclear which materials were used in a building's construction and therefore the identification of fire retardants is not clear, thereby complicating the recycling process.

The statement about the difference from packaging polystyrene to construction polystyrene was interesting. "It was mentioned by a representative of the company that packaging polystyrene is allowed to be sold, whereas construction-grade polystyrene, if fresh and clean, is considered waste and is not allowed to be sold as of it's potential contamination. EPS that can be recycled is shredded, stored in silos, and eventually mixed with cement as an aggregate or transformed into boards in thermobound. Legally, all polystyrene foams that can be proven to be construction-grade must be treated as such. If there is no proof of its shredability or composition, it is classified as hazardous waste, although it's often evaluated for potential recycling and processed accordingly."

XPS, known for its hardness and often branded as Styrodur, presents its own set of challenges. Without clear identification, it cannot be recycled and is deemed hazardous waste, requiring incineration at facilities in Vienna. Current regulations prohibit the processing of XPS without proof of composition such as an environmental product declaration (EPD), leading to its temporary storage at waste management facilities until proof of composition is provided.

The interview also touched on the broader issue of construction and demolition waste management. It emphasized the importance of better sorting and separation at the demolition stage to reduce disposal costs and improve material identification for recycling purposes.

Furthermore, the conversation highlighted the strict regulations surrounding Persistent Organic Pollutants (POPs) [21]. These substances, regulated both at the EU level and globally, must be carefully managed in waste treatment to prevent environmental and health hazards. Waste containing or contaminated by POPs requires specialized treatment to destroy or irreversibly transform the pollutants, ensuring the remaining waste does not exhibit POP characteristics.

This discussion with the waste management company offers valuable insights into the complexities of recycling EPS and XPS in Austria, illustrating the intricate processes and regulatory challenges involved in striving for a more sustainable and environmentally responsible waste management practice.

3.3.2. Solvent Based Recycling - PS Loop (Netherlands)

In contrast to the challenges faced in Austria, the Netherlands is actively embracing innovative recycling technologies. PS Loop, a recycling company based in Terneuzen, has developed a pioneering solution known as the CreaSolv® demonstration plant to address the recycling of EPS contaminated with the banned flame retardant hexabromocyclododecane (HBCD). This initiative not only reflects the Netherlands' commitment to environmental sustainability but also highlights the potential of technological innovation to overcome barriers in the recycling of construction materials.

The CreaSolv® process, developed in collaboration with the Frauenhofer Institute IVV, is a groundbreaking solvent-based method that selectively dissolves EPS while minimizing impurities. This approach is specifically designed to address the challenge of recycling EPS insulation waste contaminated with HBCD, a persistent organic pollutant banned in 2013 due to its environmental and health hazards.

The process consists of the following steps:

- Dissolution: Sorted and shredded EPS waste is dissolved in the CreaSolv® solvent, which selectively targets the polystyrene polymer while leaving behind contaminants like HBCD.
- Cleaning: The solution is then purified, separating out insoluble impurities, which are either disposed of or recycled.
- Precipitation: Changes in solvent properties cause the polystyrene to precipitate out as a gel.
- Extrusion: The recovered polystyrene gel is dried and extruded into new plastic granules, ready for reuse.
- Distillation and regeneration: The solvent is distilled and regenerated for reuse in the recycling process, making it a closed-loop system.

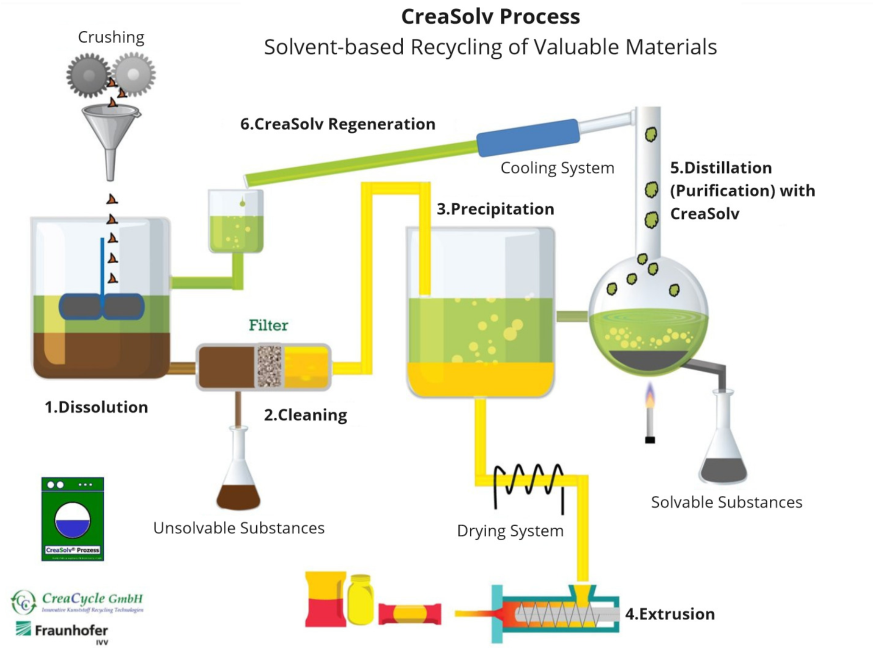


Figure 3.5: CreaSolv® process [23]

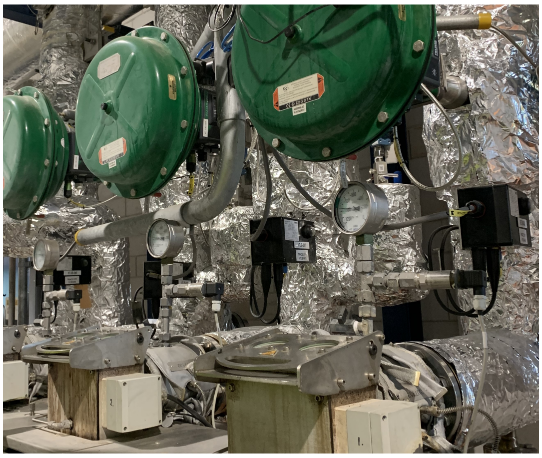
This process is a significant advancement in EPS recycling because it efficiently maintains the chemical structure of the polymers, enabling their reuse in similar applications. Furthermore, it is one of the few solvent-based methods capable of handling HBCD contamination, ensuring that the recycled material meets stringent international environmental standards.

Interviews with PS Loop's CEO and CTO, along with a site visit to the Terneuzen facility, provided valuable insights into their recycling operations. They emphasized that the CreaSolv® process can handle upto 10% contaminated EPS, including material that is up to approximately 60 years old. While XPS recycling presents additional challenges due to the need for CFC removal, EPS recycling is comparatively straightforward with the CreaSolv® technology.

Economically, PS Loop emphasises, that the process is advantageous due to substantial cost savings compared to incineration. In Germany, for example, incinerating for HBCD containing material a ton of EPS can cost as much as €8,000, while the annual cost for the dissolution process at PS Loop is approximately €45,000 for 3,000 tons of material. In other countries such as Belgium incineration can be a lot cheaper and therefore less attractive for construction waste coming from there. This highlights the potential financial benefits of recycling over traditional waste disposal methods.

(a) Density Separation Vessel

(b) Precipitation Reaction



(c) Extrusion

(d) Granulate

Figure 3.6: Various processes and apparatus at PS Loop

PS Loop's facility in Terneuzen is designed with a focus on environmental sustainability and resource efficiency. The plant features a three-level design with various silos, vessels, containers, and processes aimed at achieving zero wastewater output. Additionally, the materials received by PS Loop are primarily compacted, which significantly reduces transportation costs.

During the site visit, various processes and apparatus were observed (Figure 3.6), including the density separation vessel (Figure 3.6a), the precipitation vessel (Figure 3.6b), and the extruder used to create the final recycled EPS granules (Figure 3.6c, 3.6d). The plant, designed for zero wastewater output, is an example for a circular approach to resource utilization. Materials received by PS Loop are primarily compacted, minimizing transportation costs, and sourced from regions with high incineration costs, maximizing economic benefits. PS Loop holds a unique license for transporting HBCD across borders, further expanding their operational reach.

The company sources much of its material from Germany and Austria, where incineration costs are considerably higher than in the Netherlands. This strategic approach not only maximizes economic benefits but also contributes to a more sustainable waste management solution for these regions. Due to regulatory constraints on the cross-border transport of HBCD, PS Loop has obtained a unique license allowing them to transport these materials internationally, further expanding their operational reach.

The site visit revealed that the facility was still in its early stages of operation, transitioning from laboratory-scale experimentation to industrial-scale trials. While the design capacity aims for 20 tons per week, the current output is around 5 tons per week as the company fine-tunes the process and addresses operational challenges.

Despite its promising potential, the CreaSolv® process faces certain limitations. The recycling process can shorten polystyrene chains, limiting the material's recyclability to five cycles before it becomes too brittle for reuse. Additionally, the recovered EPS may exhibit slightly lower performance compared to virgin material due to increased spacing between polymer structures.

However, with upcoming regulatory changes requiring EPS producers to incorporate at least 5% recovered EPS by 2025 and the EU's goal of eliminating new EPS production by 2050, the importance of efficient EPS recycling technologies like CreaSolv® cannot be overstated. PS Loop's initiatives and technological advancements in this field are crucial steps towards achieving a more circular and sustainable EPS and XPS industry.

The company's ambitious goal of scaling up its recycling capacity to 10,000 tons annually, along with continued support from the Dutch government and collaborations with industry partners, highlight the growing momentum and potential of solvent-based recycling as a viable solution for managing EPS waste.

3.3.3. Waste Management - van Werfen (Netherlands)

The company collaborates with various partners to manage and recycle construction waste, specifically plastics. Despite not recycling EPS or XPS themselves, they have established a partnership with Niewpoort, a recycling company in the Netherlands, to handle EPS. Their recycling process involves several steps to ensure the material is adequately prepared for remanufacturing.

At the waste management facility, waste is manually sorted to separate different types of materials. This includes various plastics like polypropylene (PP), polyvinyl chloride (PVC), acrylonitrile butadiene styrene (ABS), and polystyrene (PS), but not EPS and XPS. The sorted plastics are then shredded and washed. Following the washing, the material undergoes a detailed lab analysis to confirm its suitability for recycling.

The company also employs mobile shredders and grinders, enhancing their flexibility to manage waste directly on-site. This ability to mobilize equipment minimizes the need for transporting materials over long distances, thus reducing the environmental footprint of their operations.

They obtain materials primarily from municipal waste management companies not a lot from construction companies, focusing mostly on the recycling of plastics used in municipal settings. With an annual handling capacity of up to 65,000 tonnes of material, the company stands as a significant recycling company in the regions of the Netherlands and Belgium.

In pursuit of innovative recycling techniques, they are engaged in a "moonshot" project aimed at increasing the types of recyclable plastics. This project involves advanced separation techniques, including manual sorting, infrared technology, density separation using water and salt solutions, and processes such as shredding, washing, regrinding, and micronizing to ensure the thorough processing and recycling of plastic materials.

3.3.4. Conclusion

Both countries face challenges in the waste management and recycling of EPS and XPS. The high costs of incineration in Austria and the complexities of separating contaminated materials pose significant hurdles. The Dutch company Van Werfen focuses on general plastic recycling, partnering with others for EPS, while the Austrian company Rossbacher is confronted with complex regulations and material identification issues. PS Loop in the Netherlands showcases an innovative solution with its CreaSolv® process, offering a promising approach to recycling contaminated EPS, but its scalability and broader adoption remain to be seen.

4

Recycling Challenges of Bitumen Contaminated EPS

Bituminous membranes, commonly used in roofing, pose significant challenges for recycling due to their adhesive nature and complex composition when combined with EPS insulation. This chapter investigates the feasibility of recycling EPS contaminated with bitumen, a common issue in construction waste. The analysis focuses on material from a demolished building in Austria, highlighting the difficulties in separating bitumen from EPS. Laboratory tests reveal that manual and mechanical separation methods are labor-intensive, ineffective and often not successful. The study emphasizes the need for innovative recycling technologies and more sustainable construction materials to address the challenges posed by bitumen-contaminated EPS waste.

4.1. Bitumen Contaminated Material

To address industry concerns about the feasibility of recycling bitumen-contaminated EPS waste, this study analyzed materials from a 1970s building demolished in Austria in February 2024. The complex waste generated, particularly EPS contaminated with bitumen, poses environmental and financial challenges due to the difficulty of separation and increased disposal costs. It is difficult to separate this material due to their adhesive properties. Figure 4.1 illustrates the intricate layering of these materials, highlighting the need to assess the feasibility of repurposing and explore advanced techniques for recycling such complex composites.

Objectives of the Analysis:

- Assessing separability: To understand the ease or difficulty of separating EPS insulation from the bituminous membrane in a real-world scenario. The literature and industry review had identified bitumen contamination as a major obstacle to EPS recycling, hence the need to practically evaluate the separation process.
- Evaluating recyclability: To determine the potential for recycling the recovered EPS in applications like asphalt modification. This involved assessing the purity of the separated EPS and identifying any limitations posed by the presence of additives or other contaminants.

The tested material, originating from a building representative of typical late-20th-century construction practices in Austria, lacked detailed documentation on the exact materials. This lack of information, common in older buildings, necessitates thorough analysis to determine material composition before considering recycling or reuse. The roofing material combined a bituminous layer with EPS insulation as depicted in figure 4.1, a common practice that, while enhancing insulation and moisture protection, poses challenges for separation and recycling due to the difficulty of separating the composite materials.

Upon investigation, the material displayed significant heterogeneity, not only in the transition from EPS to bitumen but also within the EPS itself. As illustrated in figure 4.1, the EPS exhibited variations in color and transparency, suggesting potential differences in material formulation over time. This heterogeneity raised questions about the precise composition of the EPS and underscored the need for detailed analysis to determine both the overall material composition and effective separation strategies for recycling.

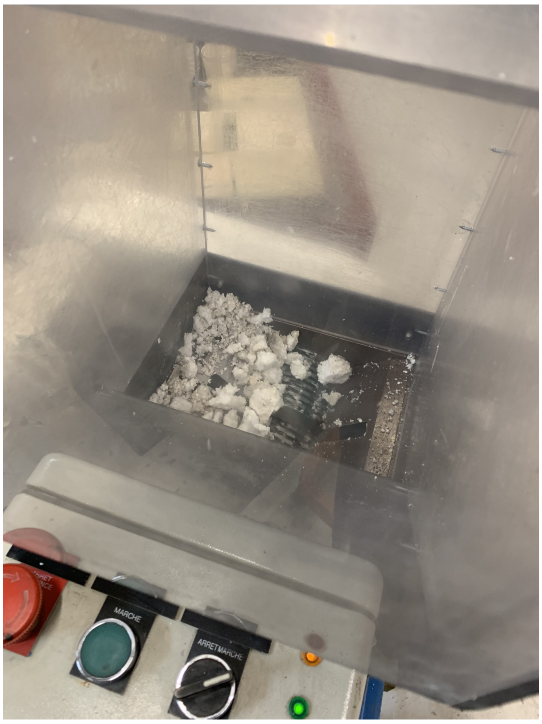
Figure 4.1: Bitumen EPS layering structure

4.2. Detailed Analysis and Testing Procedures

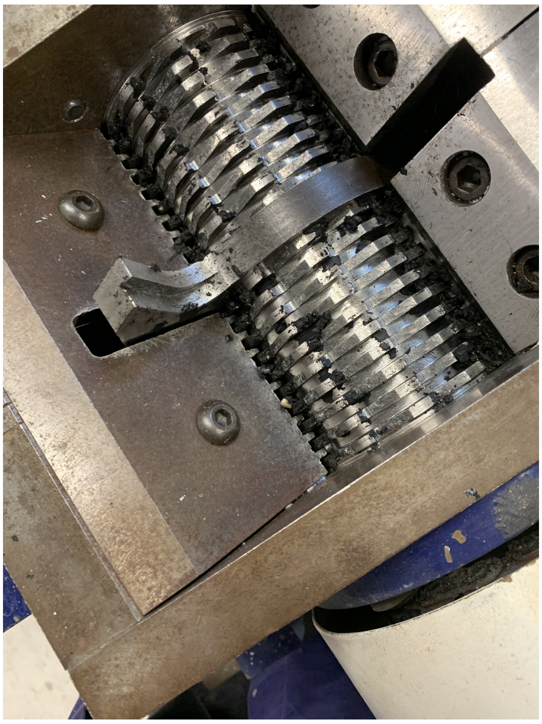
Prior to processing the demolition waste, milling techniques were refined using raw EPS. Initial trials with a plastic cutting mill successfully processed virgin EPS. However, alternative methods like rolling mills or other crushers either flattened the material excessively or failed to crush it sufficiently. As most machines required smaller starting material, the cutting mill was primarily used for further processing.

The analysis of the material generated at the demolition site began with the material undergoing an initial mechanical crushing process. The material, as depicted in figure 4.1, consists of a white EPS insulation layer and a black bituminous layer. The focus was primarily on recovering the EPS, which was seen as potentially useful for further applications, depending on its purity and the nature of additives and fire retardant layers present.

To mitigate contamination of the cutting mill, the majority of the bituminous layer was manually removed from the EPS insulation using a knife. While this initial separation was successful, it proved to be labor-intensive and incomplete, as some bitumen remained adhered to the EPS. The partially cleaned material was then processed in the ”MODITEC PLASTIQUE cutting mill” (figure 4.2c). Initially, the crushing process proceeded smoothly (figure 4.2a). However, as the machine operated, the residual bitumen melted due to the increasing temperature and adhered to the blades (figure 4.2b), hindering the operation and necessitating frequent stops for cleaning. The resulting mixture of crushed EPS and bitumen is shown in figure 4.2d. Following the complications with the cutting mill, further attempts were made using other milling and crushing equipment available in the lab. These included trials, which did not effectively process the material due to its inability to separate the compounded layers. These challenges underscored the complexity of recycling composite materials like EPS contaminated with bitumen and the need for more specialized separation techniques.

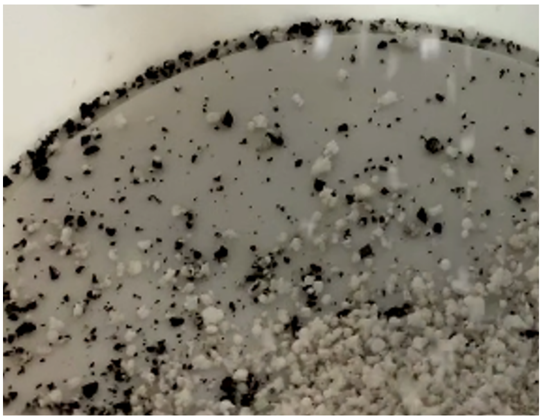


(a) Crushing of EPS contaminated with bitumen using a plastic cutting shredder



(b) Cutting part of the mill - contaminated with bitumen due to heat

(c) Machine specifications



(d) Outcome different sizes of Bitumen and EPS

Figure 4.2: Different pictures from the process of trying to downsize and crush the EPS that is contaminated with bitumen

To assess the feasibility of separating bitumen and EPS using common techniques, various separation methods were tested on the crushed material. Attempts included density separators utilizing both water and air systems. However, these efforts were hindered by the similar densities of bitumen and EPS, compounded by the cross-contamination of EPS with bitumen during the crushing process. The inability to achieve satisfactory separation raised concerns about the feasibility of recycling this composite material and further enhancing the view of the industry, which is not processing this material further.

Given the difficulties in mechanical processing and separation, the scope of the work was reevaluated. Tests such as Differential Scanning Calorimetry (DSC) and Fourier Transform Infrared Spectroscopy (FTIR) were conducted on the isolated EPS samples to assess their properties and compare them against known standards of EPS. These analyses aimed to establish the material's suitability for further applications and its overall purity.

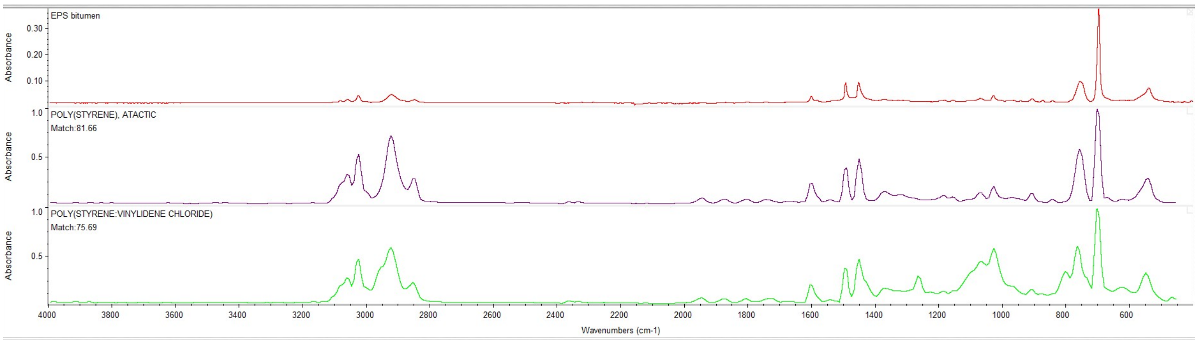
Further testing included setting a small sample on fire to determine the presence of fire-resistant substances. The material did not inflame, confirming the addition of fire retardants. DSC and FTIR tests were also performed, revealing the material's complex composition.

These findings underscore significant challenges in recycling complex construction materials, such as bitumen and EPS, which are compounded by their intricate compositions and strong adhesive properties. Despite sophisticated attempts at separation and analysis, efficient material recovery remains elusive with current technologies.

4.3. Material Tests FTIR and DSC

To better understand the properties of the EPS parts of the provided material—sourced from a building constructed around 1970 without product declaration—and to assess the presence of additional substances, Differential Scanning Calorimetry (DSC) and Fourier Transform Infrared Spectroscopy (FTIR) tests were conducted on the EPS isolated from the bituminous parts. These tests were conducted to gain further insights into the material's composition and properties, due to the lack of documentation.

FTIR analysis, which measures the absorbance of infrared light to identify molecular bonds and functional groups, revealed an 81% overlap with a reference polystyrene sample (figures 4.3 and 4.4). This high degree of similarity confirms the primary constituent of the EPS is indeed polystyrene. However, the remaining 19% of the spectrum indicates the presence of various additives such as hydrocarbons, sulfur compounds, and alcohols.



	Index	Match	Compound Name	Library Name
1	46	81.66	POLY(STYRENE), ATACTIC	Hummel Polymer Sample Library
2	47	75.69	POLY(STYRENE:VINYLIDENE CHLORIDE)	Hummel Polymer Sample Library
3	366	75.56	BENZYL METHYL DISULFIDE, 95+%	HR Aldrich Phosphorous and Sulfur Compounds
4	320	74.40	BENZYL MERCAPTAN, 99%	HR Aldrich Phosphorous and Sulfur Compounds
5	2	72.54	Polystyrene Film	User Example Library
6	1103	71.76	TRANS-2-METHYL-3-PHENYL-2-PROPEN-1-OL, 95%	HR Aldrich Alcohols and Phenols
7	644	71.32	BIBENZYL, 99%	HR Aldrich Hydrocarbons
8	847	68.21	BETA-BROMOISOPROPYLBENZENE, 99%	HR Aldrich Hydrocarbons
9	626	67.22	BUTYLBENZENE, 99+%	HR Aldrich Hydrocarbons
10	1096	66.12	4-PHENYL-1-BUTANOL, 99%	HR Aldrich Alcohols and Phenols

Figure 4.3: FTIR analysis

These differences are evident in the full overlapping figure (Figure 4.4) and the zoomed-in spectra around wavenumbers 3,000 [cm-1] and 1,500 [cm-1] in figures 4.5a and 4.5b, which highlight distinct differences not present in the reference EPS. These spectral variations suggest the potential for unique chemical compounds or modified chemical structures within the EPS sample compared to standard EPS. While a more thorough investigation of these differences could reveal the specific nature of the additives, this was not pursued in the current work, as the material was deemed unsuitable for further processing due to the challenges in separating EPS from the bituminous matrix in the first place which make an end of life application not possible.

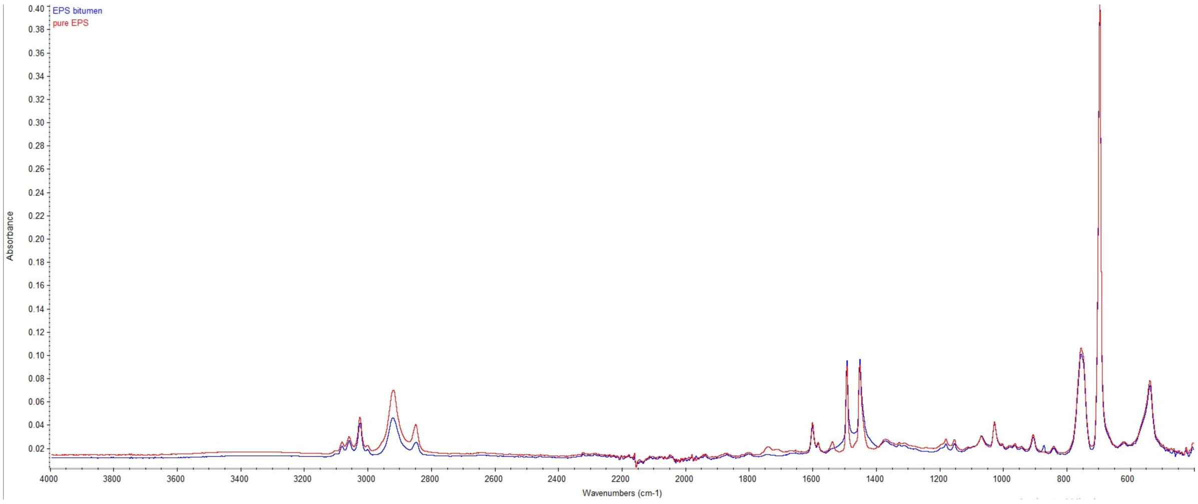
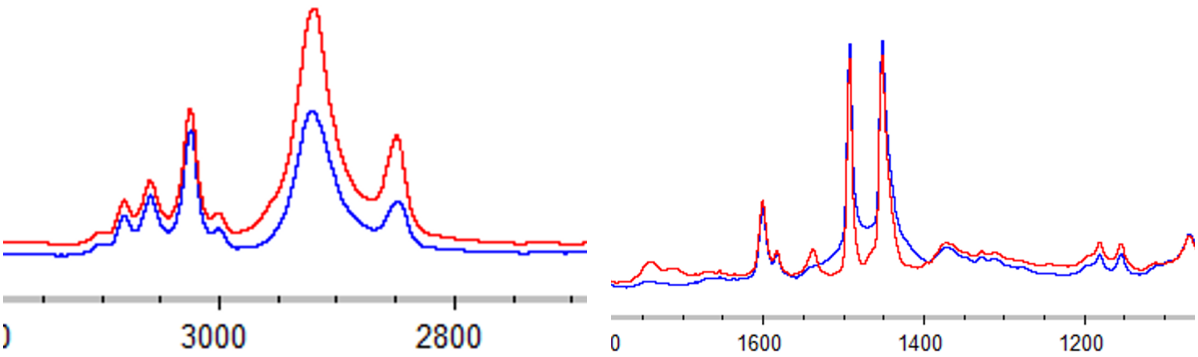


Figure 4.4: EPS overlapping comparison
the blue line is indicating the recovered EPS from the construction waste
the red line is indicating the EPS which is newly bought



(a) Zoom around 3000 [cm-1] of overlapping comparison

(b) Zoom around 1500 [cm-1] of overlapping comparison

Figure 4.5: Combined overlapping comparisons

Differential Scanning Calorimetry (DSC) analysis reveals the thermal behavior of the EPS bitumen sample (figure 4.6). Two distinct endothermic peaks are observed, indicating energy absorption as the temperature increases.

The first peak, centered around 250.80°C, corresponds to the melting point of polystyrene, which typically occurs between 264-272°C [66]. This peak aligns with the expected behavior of polystyrene in DSC analysis, signifying the transition from a solid to a liquid state. The associated energy change, while less pronounced than the second peak, indicates the energy required for this phase change.

The second peak, centered around 421.72°C, corresponds to the degradation point of polystyrene, which typically occurs between 341–441°C [67]. This peak aligns with the expected behavior of polystyrene in DSC analysis, signifying the breakdown of its structure. The associated energy change, with an area of 4911.0897 mJ and ΔH of 489.6400 J/g, signifies a substantial energy input required for this degradation process.

The observed thermal transitions, aligning with the known melting and degradation points of polystyrene, confirm its presence as a major component of the EPS bitumen. The presence of these two distinct peaks indicates the complex thermal behavior of the EPS bitumen, which is influenced by the interaction of different components and their individual thermal properties. These findings are crucial for understanding the material's thermal stability and its suitability for applications where durability and thermal resistance are essential.

Thermal Property	Description	Value	Unit	Source
Glass transitioning point	Temperature at which polystyrene transitions to a glassy state	100	°C	[68]
Melting point	Melting point range of polystyrene	264–272	°C	[66]
Degradation interval	Degradation interval of polystyrene	341–441	°C	[67]

Table 4.1: Thermal properties of polystyrene.

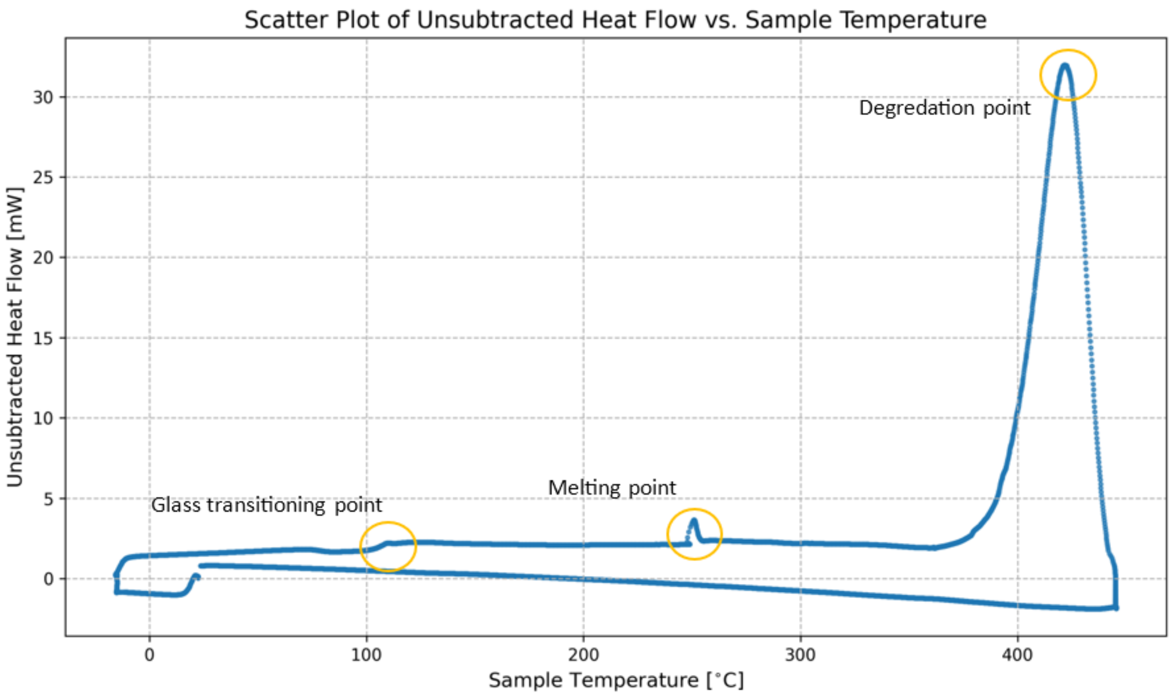


Figure 4.6: DSC analysis recycled EPS

This chapter highlights that bituminous membranes, a common roofing material, present significant recycling challenges due to their adhesive properties and complex composition when combined with EPS insulation. Laboratory tests demonstrate that separating bitumen from EPS is labor-intensive and often ineffective. The analysis of materials from a demolished building in Austria further exemplifies this issue, revealing significant bitumen contamination that interfere recycling. Attempts to separate the materials were met with operational difficulties due to bitumen's adhesive nature.

The analysis of EPS bitumen samples using DSC and FTIR reveals valuable insights into the material's thermal behavior and composition. While the DSC and FTIR analysis are straightforward to perform, it is challenging to determine the exact composition of the material and identify potential contaminants. Despite these complexities, the DSC and FTIR analysis suggests that the tested material closely resembles standard virgin EPS material and may not contain HBCD or other contaminants. The presence of the distinct melting and degradation points of polystyrene observed through DSC, and the characteristic FTIR spectra, strongly indicate a relatively pure EPS composition. The observed parameters of the tested material are consistent with the known parameters of polystyrene this provides evidence that polystyrene is a major component of the harvested EPS with bitumen.

4.4. Conclusion

Construction waste streams containing EPS and XPS insulation contaminated with adhesives such as bitumen pose significant recycling challenges. The case study of bitumen-contaminated EPS demonstrates the limitations of existing recycling methods, as complete separation proved unsuccessful. Laboratory analysis confirmed the complex composition of the recovered EPS, further complicating recycling. These findings highlight the need for innovative recycling technologies tailored for contaminated construction waste and sustainable construction practices that prioritize deconstruction and the use of easily recyclable materials.

5

Proposed Recycling Strategies

This chapter proposes strategies for recycling and reusing EPS and XPS waste in the construction industry, addressing the challenges posed by different contamination levels. For uncontaminated waste, collaboration with initiatives like EPSolutely and direct sales to EPS and XPS producers are recommended. For EPS and XPS contaminated with glue and mortar, mechanical recycling at facilities like KBM in Denmark is advised, while solvent-based recycling at PS Loop in the Netherlands is suggested for HBCD-contaminated materials. The chapter also discusses the challenges of recycling bitumen-contaminated EPS, advocating for the development and use of alternative materials with lower environmental impact or easier separation. Additionally, it emphasizes the importance of designing for recyclability by choosing materials and methods that facilitate end-of-life recycling.

5.1. Strategies for Off Cuts - Construction Waste

This part expands on the previously discussed waste stream of offcuts and surpluses introduced in chapter 2, exploring alternative strategies for managing these materials beyond conventional disposal methods. Recognizing the inherent value of these offcuts, the construction company has implemented segregation practices to distinguish them from other waste streams. The goal is to identify improved practices that enhance sustainability and provide economic benefits by reducing disposal costs and reutilizing valuable resources.

One effective strategy for better managing EPS and XPS offcuts waste is to participate in pilot projects initiated by EPSolutely presented in chapter 3, which focus on collecting EPS materials either directly at construction sites or through local hubs. This initiative offers two main approaches: On-site collection and local hub collection. On-site collection, which is ideal for larger quantities of EPS offcuts, involves direct collection from your construction site using EPSolutely bags. This service is provided by Austrian insulation producers (Austrotherm, Steinbacher) and typically ensures pickup within five business days once five bags are filled. Collection at local hubs, this option is well-suited for sites generating smaller amounts of EPS waste or sites where EPS cannot be stored. Filled EPSolutely bags are transported to a designated hub, with collection occurring within five business days once 20 bags have accumulated. The problem with this option could be that the nearest hub may be a considerable distance from the primary location and is about 100km away from the main office of FREY construction site.

Both on-site and hub-based collection strategies have distinct advantages. On-site collection allows for rapid turnover and minimizes contamination by immediately segregating EPS waste. The hub-based approach is more efficient for small-scale operations, centralizing waste accumulation and potentially reducing the frequency and cost of pickups. This initiative adds value to EPS offcuts by facilitating their collection and recycling.

Another strategy involves collaborating with EPS and XPS material producers. Many producers are willing to reclaim their products for reintegration into their production cycles. By returning EPS and XPS offcuts directly to the original manufacturers, the construction company ensures efficient and sustainable recycling. This closed-loop system not only reduces waste but also lowers the environmental impact associated with producing new materials from scratch. Producers often have established recycling processes and the necessary equipment to handle large volumes of returned materials, making this a practical and environmentally sound option. Companies such as SUNPOR, HIRSCH, and AUSTROTHERM are known to accept returns of their materials, and some already supply FREY. Contacting these suppliers directly to inquire about their reclamation programs could be a beneficial step towards waste reduction and potential revenue generation.

Another option for managing EPS and XPS offcuts is to sell them directly to companies that produce and specialize in recycle these materials as mentioned in chapter 3. To ensure a successful sale, maintaining the integrity and traceability of the offcuts, including documentation like EPD, is crucial. This demonstrates that the material is free from contaminants and meets the necessary quality standards for reuse. By selling directly to such companies, construction firms can not only reduce waste but also potentially generate revenue from materials that would otherwise be discarded.

However, it is important to note that this practice is less environmentally friendly and does not fully contribute to a circular economy, as it involves downcycling. Once EPS is used in concrete, for instance, the material cannot be easily recycled again due to the lack of established separation processes. Consequently, while this option offers financial benefits, the long-term environmental impact must be carefully considered, as EPS does not biodegrade and can contribute to persistent pollution if not properly managed.

Both collaboration with material producers and direct sales to EPS and XPS producing companies can provide financial benefits by reducing disposal costs and potentially generating income. These strategies promote sustainability by minimizing the volume of waste sent to incineration or landfills. Engaging directly with material producers and EPS manufacturing companies offers a streamlined approach to waste management, ensuring that EPS offcuts are recycled or reused in the most efficient manner possible.

5.2. Strategies for Glue and Mortar Contaminated Material - Demolition Waste

This section outlines methods for processing contaminated materials without incineration, specifically focusing on the company FREYs waste generation. The objective is to recycle contaminated EPS and XPS materials, such as glue, mortar and plaster effectively. This includes strategies for handling EPS and XPS, which have significant environmental impacts (approximately 3,000 kg CO2 Eq per tonne when incinerated) as seen in Chapter 6 and high recycling value. The aim is to establish better recycling practices for these materials.

Implementing recycling strategies can be challenging for construction companies, as decisions are often influenced by external factors such as the practices of recycling and waste management entities. Materials contaminated with substances like glue and mortar, and similar compounds (as discussed in 2.3.3) should be separated on-site. FREY already treats these materials differently from uncontaminated ones.

For buildings constructed before 2016, the fire retardant HBCD was likely used in the production of EPS and XPS, indicating solvent-based recycling as the best option. For buildings constructed after 2016, mechanical recycling is preferred. HBCD-containing materials must be incinerated or solvent-recycled, as reintroducing HBCD into the cycle is prohibited [21]. Which recycling route to take can only be known if the EPDs are available. Therefore it is recommended that the company monitors EPDs when purchasing and installing insulation panels, which dictate the appropriate recycling route.

To optimize recycling, materials should be sorted on-site during demolition. While this process can be labor-intensive and costly, it's essential for effective recycling. The company is advised to crush and separate materials on-site, reducing the need for intensive processes in waste management.

Using machinery like the ”WEIMA Zerkleinerer” Model: WLK [69] for crushing and the ”UMS Lufttrennherd” Model: ARJ [70] for separation can effectively reduce contamination levels to lower than 10%. The mobility of these machines, allow on-site processing, making transportation more efficient and less costly.

When material is in need for further recycling and therefore also for transportation, compaction is advised to lower the transportation costs. Compacting materials using mobile units like the ”FZ-Recycling compaction tool” or the ”EPSTEC Compaction unit” significantly increases material density. For instance, EPS density can increase from 20 kg/m³ to 200 kg/m³ after densification [71], enhancing structural integrity and facilitating handling.

Detailed implementation steps:

- Monitoring product declarations: Construction companies should closely monitor product declarations when purchasing and installing insulation panels. These declarations provide critical information about fire retardants and other additives, which determine the recycling route.
- On-site sorting: During demolition, materials should be sorted accurately. Similar materials should be grouped together to facilitate efficient recycling. This step, though labor-intensive, is essential for reducing contamination levels and improving recycling efficiency.
- Crushing and separation: Utilizing machinery like the WEIMA Zerkleinerer and UMS Lufttrennherd for on-site crushing and separation will help achieve contamination levels below 10%. These machines are effective in processing large volumes of material and can be transported to different demolition sites as needed. For smaller material volumes as well as for demolition material that is not very contaminated these set of machines would also be enough for recycling. Therefore also new materials that end up being less contaminated are advised to use.
- Compaction: After separation, materials should be compacted to reduce volume and transportation costs. Mobile compaction units, such as the FZ-Recycling compaction tool or the EPSTEC Compaction unit, are recommended for this purpose. These units increase material density, making it easier to handle and transport.
- Transportation: Once compacted, materials can be transported to designated recycling facilities. For solvent-based recycling, materials are sent to PS Loop in the Netherlands. For mechanical recycling, materials are sent to KBM in Denmark. Both facilities are equipped to handle large volumes of compacted EPS and XPS.
- Recycling process:
  - Mechanical recycling: Involves shredding, washing, and pelletizing materials. This method is less intensive and suitable for newer materials without HBCD.
  - Solvent-based recycling: Involves treating materials with solvents to remove contaminants and purify EPS and XPS. This method is suitable for older materials containing HBCD.

Effective recycling of contaminated EPS and XPS materials requires a comprehensive approach involving on-site sorting, processing, compaction, and transportation. By adopting these strategies, FREY can enhance its recycling practices, reduce environmental impact, and manage logistical challenges more efficiently. Through diligent monitoring of product declarations, utilizing advanced machinery, and partnering with specialized recycling facilities, FREY can contribute significantly to sustainable construction practices and the circular economy.

Proposed Mechanical Recycling

FREY is advised to utilize the KBM [72] recycling process in Denmark for their mechanical recycling needs. This facility is highly regarded within the european construction industry, having been utilized by numerous companies and recommended by material suppliers. Moreover, KBM is one of the few facilities of its kind in Europe. Despite the considerable transportation distance, the quality and machinery sequences of the KBM process make it the recommended choice.

The mechanical recycling process at KBM [72] for EPS involves several stages, each utilizing specialized equipment to ensure efficient recycling and high-quality output. A similar process for XPS is currently under development, with an additional machine being integrated for XPS recycling, it is currently in a testing phase and not yet widely used. Figure 5.1 provides an overview of the main steps. The machinery used in this process is available in different series, including the MINI, MAXI, and JUMBO recycling lines. Depending on the contamination level as well as the volume of material one of these series is being used. Each series involves all the necessary steps but varies in capacities and electrical

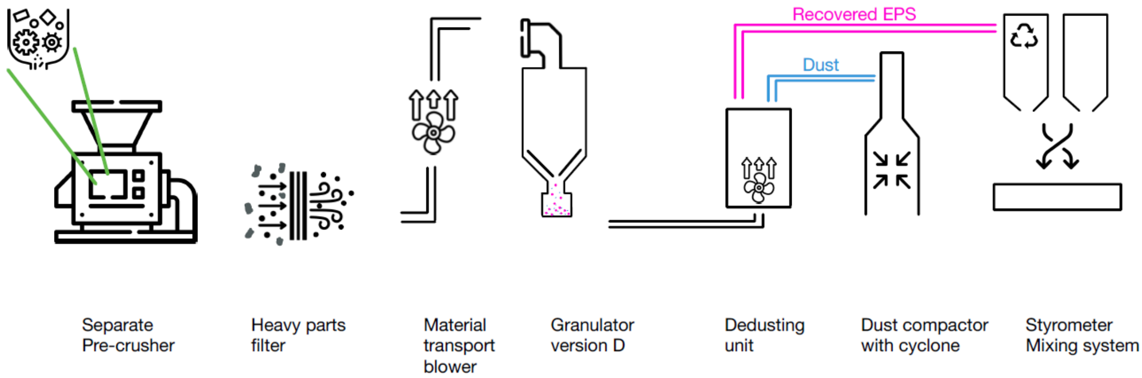


Figure 5.1: MAXI LINE - mechanical recycling by KBM recycling

loads, with the MINI line handling the lowest capacities, the MAXI line mid-range capacities, and the JUMBO line the highest capacities and loads.

The process begins with the Separate Pre-crusher, designed to reduce large EPS scrap into smaller, more manageable pieces. This stage is crucial for preparing the material for subsequent processing. The pre-crushers are available in various models, each catering to different capacities. The pre-crushers used in the process have capacities ranging from 8 to 100 m³/hour, with electrical loads between 7.7 kW and 16.72 kW. These machines are designed to process both normal and compacted EPS efficiently. For normal EPS, they can handle 500-600 kg/hour, whereas for compacted EPS, they can process 5000-6000 kg/hour, demonstrating their versatility and efficiency in handling different material densities.

Following pre-crushing, the material passes through a Heavy-parts Filter. This filter removes heavy contaminants such as dirt and concrete, ensuring that the EPS material is nearly 99% pure. The filter has a capacity of over 40 m³/hour and helps prevent damage to subsequent processing equipment [72].

The cleaned EPS is then transported via a material transport blower to the granulator, ensuring continuous and efficient movement through the recycling line. The granulator further reduces the size of the EPS particles, preparing them for the de-dusting stage. Different models of the granulator cater to various capacities. The granulator systems have varying capacities and electrical loads depending on the specific model used. The capacities range from 6 to 40 m³/hour, with electrical loads between 19 and 36 kW. These systems are designed to efficiently reduce EPS particle size, preparing them for further processing [72].

The separate de-dusting unit is critical for removing fine particles and dust from the granulated EPS material. This unit increases the quality of the recycled material and prevents production stops due to dust accumulation. The de-dusting units have capacities ranging from 8 to 40 m³/hour, depending on the specific model used. These units efficiently remove fine particles and dust from the granulated EPS material, enhancing the quality of the recycled product [72].

Dust removed during de-dusting is compacted using a dust compactor with cyclone, which compacts the dust into dense rods, reducing waste volume and facilitating easier disposal. The dust compactor with cyclone is integrated into the system, typically with an electrical load of around 2.2 kW [72].

The final stage involves the styrometer mixing system, which accurately meters and mixes recycled EPS with virgin beads, ensuring a precise mixing ratio. This system is crucial for maintaining product quality. The styrometer operates with an electrical load of around 4.0 kW and is available in various capacities. The styrometer mixing systems have capacities ranging from 6 to 40 m³/hour [72].

The mechanical recycling process at KBM efficiently converts EPS waste into high-quality recycled material. Each stage utilizes specialized equipment designed to handle large volumes, minimize dust, and ensure the purity of the recycled material, making it a sustainable solution for EPS waste management. For further analysis, particularly in the Life Cycle Assessment (LCA) in Chapter 6, the MAXI LINE will serve as the reference due to its current use by Austrian waste management companies.

Table 5.1 summarizes the different capacities, mass processed, electrical load, and energy consumption of the MAXI LINE equipment, highlighting its performance with both normal (orange) and compacted (blue) EPS. This process will be further examined in Chapter 6 for the Life Cycle Inventory.

MAXI Model	Capacity [m^3/hour]	Mass Processed [kg/hour]	Electrical Load [kW]	Energy Consumption [kWh/kg]
Separate Pre-crusher	25-30	500-600 5000-6000	8.8	0.0146-0.0176 0.0014-0.0017
Heavy-parts Filter	+ 40	Not specified	Not specified	Not specified
Granulator (Version D)	10-12	200-240 2000-2400	36	0.15-0.18 0.015-0.018
Separate De-dusting Unit	18-20	360-400 3600-4000	Integrated into system load	Integrated into system load
Dust Compactor with Cyclone	Integrated into system	Integrated into system	2.2	Integrated into system load
Styrometer Mixing System	10-12	200-240 2000-2400	4.0	0.0167-0.02 0.0017-0.002
Total	10 - 12	200-240 2000-2400	51	0.1813-0.2167 0.0181-0.0216

Table 5.1: Summary of maxi line models, capacities, mass processed, electrical load, and energy consumption. dark orange indicates normal EPS and blue indicates compacted EPS.

Proposed Solvent-based Recycling - PS Loop

PS Loop's solvent-based recycling facility in Terneuzen, Netherlands, offers the ideal solution for FREY to recycle EPS and XPS contaminated with glue, mortar, and HBCD fire retardant. Located approximately 1000 km from FREY's main office, this facility is unique in Europe, specializing in processing HBCD-containing materials, which are otherwise incinerated. By utilizing PS Loop's services, FREY can optimize resource use.

The facility receives primarily compacted materials, which significantly reduce transportation costs based on volume and weight. Sourcing mainly from Germany and Austria, where incineration costs are higher, PS Loop strategically approaches material acquisition. The facility holds a unique license for the international transport of HBCD materials, setting it apart from other companies.

The facility spans three levels and includes silos, vessels, and containers designed to achieve zero wastewater output and minimal water use. The absence of a chimney indicates that the processes do not emit fumes requiring external venting.

Transitioning from lab-scale experimentation to industrial-scale trials, the facility aims for a design capacity of 20 tons per week, currently operating intermittently at up to 5 tons per week. The recycled EPS produced has reached its first customer, although HBCD delivery to the chemical producing company IFC is pending due to licensing complications.

Solvent based recycling - PS loop

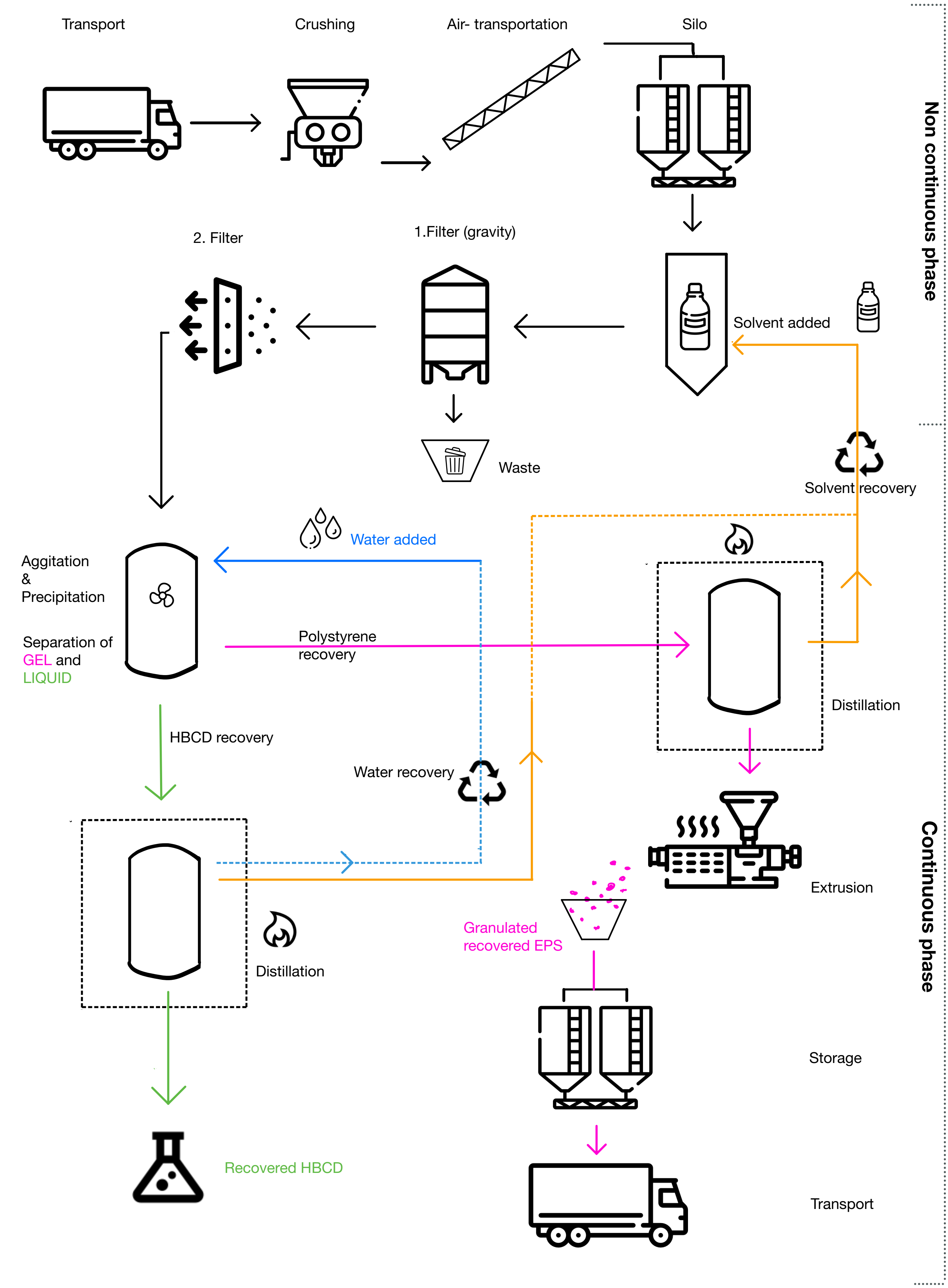


Figure 5.2: Solvent-based Recycling - PS Loop process

The PS Loop facility, as shown in figure 5.2, involves five distinct recycling phases:

1. **Non-continuous phase:**
    - **Shredding and storage:** Compacted EPS, often with 1-2% construction waste contamination, is shredded and stored in silos. Each batch, typically around 1.1 metric tons, is prepared for processing.
    - **Solvent addition and dissolution:** In the silo, approximately 7.5 cubic meters of CreaSolv® solvent, costing about €47,700 per batch, is added to 1.1 metric ton of the shredded EPS. The mixture is allowed to rest for an hour, with agitation to enhance dissolution. This process effectively separates the EPS from insoluble contaminants. The undissolved materials are then earmarked for disposal as residual waste.
    - **Dual-stage filtration:** The resulting liquid from the dissolution phase undergoes gravity filtration to remove large particles, followed by fine filtration through filters of 500 and 50 micrometers. This step separates polystyrene from contaminants.
    - **Agitation and precipitation:** The filtrate, a mixture of dissolved polystyrene, HBCD, and solvent, is placed in a vessel with a central agitator. Water is added as an antisolvent, precipitating polystyrene into a gel-like form and water and HBCD into a liquid form. This step is crucial for polystyrene recovery and HBCD extraction. The ”washing procedure” to recover as much HBCD as possible, can be repeated up to five times, depending on contamination levels.
    - **Transition to continuous phase:** The purified gel transitions to the continuous phase, involving concurrent operations: polystyrene recovery through solvent elimination, HBCD extraction with water and solvent removal, water reuse within the system, and solvent reclamation.
2. **Polystyrene recovery:**
    - **Heating and distillation:** The polystyrene gel, formed during the non-continuous phase, is transferred to a new vessel where high temperatures (around 400°C) are applied to distill the solvent from the gel. Two vessels operate in tandem: one for drying the gel and the other for distillation. This ensures a continuous cycle where one vessel is always in operation while the other is prepared. The distilled solvent is then reintegrated into the recovery cycle.
    - **Extrusion:** After distillation, the polystyrene still contains about 10% solvent. It is processed further in an extruder, where remaining solvent is removed through three additional distillation steps. The purified polystyrene, now in a hot, semi-molten state, is passed through an underwater extruder.
    - **Granulation and cooling:** The extruded polystyrene is rapidly cooled underwater, forming granules. These granules are then transported via an air system to storage silos.
    - **Transportation:** The granulated, recovered EPS is stored in silos until it is ready for transportation to customers.
3. **HBCD recovery:**
    - **Distillation:** The remaining HBCD-solvent mixture undergoes distillation to extract the water. This reclaimed water is reintegrated into the process.
    - **High-temperature evaporation:** The residual HBCD-solvent mixture is subjected to high-temperature evaporation at 400°C. This step removes the last traces of solvent, which cannot be recovered post-evaporation. The high temperature also releases elementary bromine.
    - **Bromine recovery:** The elementary bromine produced is collected and sold to ICL, a global manufacturer of specialty minerals.
4. **Solvent recovery:**
    - Reclamation and reuse: Solvent from various stages is reclaimed and used for heat recovery if hot, enhancing process efficiency.
5. **Water recovery:**
    - Distillation and reuse: Water is distilled and reused in the process, maintaining a closed-loop system and minimizing waste.

The PS Loop recycling process currently operates at a pilot scale, with key metrics shown in Table 6.5. These include capacity, mass processed, electrical load, and energy consumption. As the process undergoes full-scale implementation, these figures are expected to change significantly. The facility runs entirely on electricity, with an additional one-time cost of €47,700 for the dissolution process solvent. At its current capacity of 5 tonnes per week, the facility can process approximately 260 tonnes of material

annually. It's important to note that these numbers are preliminary and subject to adjustment as the upscaling process continues.
The following table summarizes the current consumption metrics:

PS Loop recycling process	**Capacity**	**Mass processed**	**Electrical load**	**Energy consumption**
	[m^3/hour]	**[kg/hour]**	**[kW]**	**[kWh/kg]**
Total	2,75	500-550	154.28	0,30

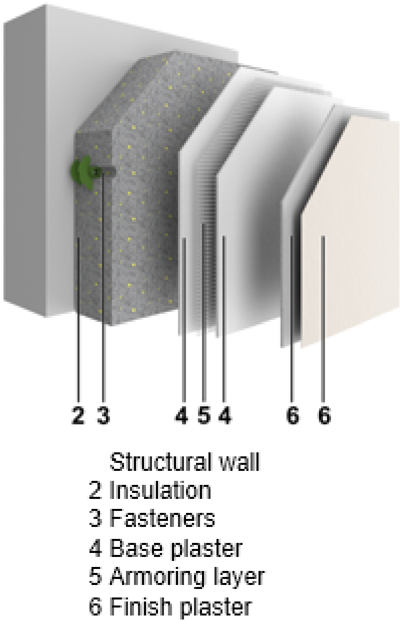
Table 5.2: Total consumption of PS Loop recycling process in: Capacities, Mass Processed, Electrical Load, and Energy Consumption.
In this process only compacted EPS is taken into account as the recycling plant only deals with compacted material blue indicates compacted EPS.

5.2.1. Strategies for Demolition

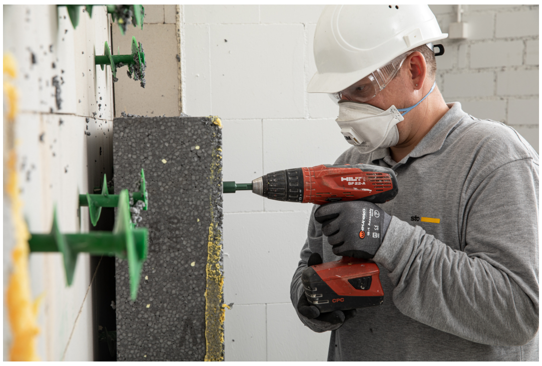
For companies aiming to enhance their sustainability practices, particularly in recycling and material reuse, it is essential to focus on end-of-life scenarios such as demolition. Current issues with ETICS are discussed in chapter 2. These systems are multi-layered constructions consisting of various chemically diverse building materials. Due to the multiple layers and the use of adhesives with insulation materials such as EPS and XPS, recycling is often not feasible due to high contamination levels. Demolition processes for these systems, as described in chapter 3, involve both manual and mechanical methods. Material separation, while challenging, is an important step in the demolition process, particularly when dealing with materials that are glued or bonded together. Manual separation is typically used for smaller quantities or when layers can be easily detached by hand, such as in floor slabs or roof insulation not affixed with adhesives. For more complex situations where materials are bonded with glue or mortar, mechanical means are essential. The company utilizes small machines and excavators for this purpose, and new technologies have been developed to enhance the separation process. Despite these advancements, separating materials bonded with adhesives remains particularly challenging, and achieving complete separation is nearly impossible.
To address these challenges, solutions that focus on better separability at the end of the life cycle of ETICS are needed. The Weber.therm circle [63] system offers such a solution. This ETICS features mostly mineral wool insulation but can also be EPS boards and mineral plasters, designed to facilitate easy separation and recycling at the end of their service life. This is depicted in figure 5.3. As seen in this figure the demolition process is as such that the layers on the outer side of the insulation can be easily separated from the insulation board. If compared to traditional demolition practices this separation cannot be made while dismounting the structure and the separation process usually starts after the demolition. The system Weber.therm circle is designed with a layer-by-layer configuration, greatly simplifying the dismantling process. The key to its ease of separation lies in its innovative use of non-bonded, mechanically fastened components and specialized separation fabrics that stabilize the plaster during dismantling, ensuring that the layers can be cleanly separated. This attribute is pivotal for recycling, allowing each material to be recovered in its pure form.

Figure 5.3: Weber.therm circle demolition practice [63]

Mineral wool is often chosen for insulation in this system primarily because of its advantageous properties. The installation of mineral wool boards is facilitated by the use of dowels, which can be inserted without compromising the material's integrity. While EPS or XPS boards can create thermal bridges by breaking down the internal structure with conventional dowels, but specialized dowels are also available for these materials, accommodating their unique characteristics. Mineral wool offers excellent thermal and acoustic insulation. Despite challenges in recycling due to health risks and its fibrous composition, recent advances in processing technologies have begun to address these issues and recycling strategies for this material are developing.
The Weber.therm circle system also includes a range of mineral coatings that enhance the system's resistance to algae and fungal growth without using biocides, making it an environmentally friendly option for facade insulation. The mineral coatings improve the durability and longevity of the insulation system, reducing the need for frequent maintenance and replacement. Additionally, these coatings contribute to better indoor air quality by preventing mold growth.
The entire system is designed for high-load mechanical durability, ensuring that it can withstand the demands of both new constructions and renovations. Its robust construction allows it to perform well under various environmental conditions, including extreme weather. By adopting systems like the Weber.therm circle for projects, construction companies can significantly enhance the efficiency of material use, ensure safer and cleaner demolition processes, and contribute more robustly to sustainability efforts in the construction industry. This approach not only improves the environmental footprint of construction projects but also aligns with modern regulatory standards and client expectations for sustainable building practices.
Another system that supports enhanced separation and recycling is StoTherm AimS® [73]. This facade insulation system utilizes EPS, XPS, or mineral wool insulation panels, which can be mechanically fixed using the StoFix Circonic fastener, allowing for adhesive-free installation. This method simplifies the demolition process in a similar method then the Weber.therm circle and ensures that materials can be cleanly separated and recycled, aligning with circular economy principles.
The StoFix Circonic, [73] a specific fixation method for insulation panels, allows for adjustments up to 70 mm to accommodate uneven surfaces, ensuring correct and secure installation even on challenging substrates. This mechanical fixation method facilitates quick and straightforward dismantling of the insulation system, allowing the components to be recycled separately without contamination.



(a) StoFix layering structure



(b) StoFix demolition

Figure 5.4: Demonstrations of StoFix structure [73]

Integrating systems like StoFix Circonic in construction projects can lead to improved environmental outcomes through reduced CO_2 emissions and enhanced recyclability. This approach preserves resources and provides a practical framework for future construction practices, contributing to sustainable development and environmental protection.
However, there are notable downsides to these materials. The primary issue is their higher cost compared to traditional ETICS methods. Typically, systems like Weber.therm circle and StoTherm AimS® are up to twice as expensive. This increased cost is due to both the higher price of materials and the additional labor costs. Workers often require specialized training to install these systems, which adds to the expense. Additionally, the installation process can be less time-efficient compared to traditional methods, further increasing labor costs.
Another challenge is the lack of widespread knowledge and adoption of these systems. Many construction companies and workers are not familiar with the specific techniques required for installation, which can lead to hesitation in adopting these new methods. Furthermore, architects and construction companies often do not advise these products because of lack of knowledge as well as the initial investment in training and the higher costs can be barriers to more widespread use, despite the long-term environmental and economic benefits. Additionally, the higher upfront costs, combined with the lack of subsidies for new construction methods and materials, can diminish widespread use despite the long-term environmental and economic benefits. These factors contribute to the slow adoption of these innovative systems, even though they offer significant advantages in terms of sustainability and recyclability.
In summary, while systems like Weber.therm circle and StoTherm AimS® offer significant advantages in terms of sustainability and recyclability, their higher costs, the need for specialized training, and the lack of awareness present challenges to their broader adoption. Balancing these factors will be crucial for the construction industry as it moves towards more sustainable practices.

5.3. Strategies for Bitumen Contaminated Material - Demolition Waste

Handling bitumen-contaminated material, as explored in chapter 2 and chapter 4, presents significant challenges due to the difficulty of separation and lack of established applications for reuse. Both chapters underscore that, unlike EPS which is not or differently contaminated, the recycling of EPS with

bituminous contamination has not yet been effectively implemented in Austria or other european countries.
Given the current limitations in separation techniques, which are difficult to implement and not widely available, the focus should shift towards developing and using new materials with a smaller environmental impact or that can be more easily separated. By adopting materials that reduce or eliminate contamination of EPS, the recycling process can be significantly simplified. This approach not only addresses the challenges posed by bitumen contamination but also aligns with broader environmental goals.
Paying attention in research and development is crucial for identifying and adopting these alternative materials. Sustainable alternatives, such as incorporating lignin as a partial replacement for bitumen, have shown promise to use on construction site. Lignin, a natural polymer abundant in plant material, is a viable alternative binder due to its chemical similarity to bitumen [74]. Studies have evaluated the mechanical properties of asphalt mixes modified with lignin [75], highlighting lignin's potential to enhance the mechanical properties of asphalt in roofing applications.
Current bituminous products on the market use highly adhesive substances that contaminate insulation boards and are not well separated. Alternatives like EPDM foil, PVC sealing, or rigid materials like metal should be considered as a possible option as they are attached with easier separable materials such as screws. Bitumen membranes are cheaper (3 to 12€ per square meter) according to standard material prices in Austria but present significant recycling challenges. PVC membranes (5 to 15€ per square meter) and EPDM foils (10 to 25€ per square meter) offer better long-term sustainability but have higher initial costs as well as are not as long lasting and more fragile and therefore not as widely used.
Encouraging the construction industry to adopt materials and methods that consider end-of-life recycling during the design phase can reduce future recycling challenges. This approach ensures that EPS, when used, remains uncontaminated or minimally contaminated, facilitating easier recycling akin to other less contaminated materials.

5.4. Challenges Implementing Recycling Strategies

The implementation of sustainable and economically viable recycling strategies for EPS and XPS waste in the construction industry faces a complex set of challenges. These challenges can be categorized into four main areas: economic barriers, logistical challenges, knowledge and adoption barriers, and regulatory and policy limitations.

Economic barriers

The economic viability of EPS and XPS recycling is hindered by several factors. Inconsistent incineration costs in Europe see table 6.10 create uncertainty for construction companies, making recycling less attractive when incineration is a cheaper disposal option. Additionally, the long distances to recycling facilities, often exceeding 1000 km, result in substantial transportation costs that can outweigh the potential economic benefits of recycling.

Logistical challenges

Logistical challenges pose significant barriers to the efficient recycling of EPS and XPS waste. The limited quantities of waste generated on individual construction sites often necessitate collaboration among multiple companies or also multiple waste managing companies to consolidate waste and optimize transportation. On-site sorting and separation of contaminated materials, while essential, are labor-intensive and costly processes that require additional resources and training for construction workers. Furthermore, achieving the required contamination levels below 10% for mechanical recycling can be difficult, necessitating specialized machinery and processes that add complexity and cost.

Knowledge and adoption barriers

The lack of awareness and knowledge about recycling options, combined with the unfamiliarity of new technologies and processes, presents a significant barrier to adoption. Many construction companies are unaware of the available recycling options and their potential economic and environmental benefits. Additionally, the adaptation to new recycling technologies and processes can be challenging for both companies and workers, requiring training and education to overcome this hurdle. The limited adoption of innovative systems like Weber.therm circle and StoTherm AimS®, despite their advantages in separation and recycling, is further hindered by their higher costs and the need for specialized training.

Regulatory and policy limitations

The absence of supportive regulatory frameworks and policies further complicates the implementation

of EPS and XPS recycling strategies. The lack of financial incentives or subsidies for sustainable construction practices, including recycling, discourages companies from investing in these initiatives. Inconsistent regulations and standards across different regions create confusion and delay the development of unified recycling practices, making it difficult for companies to navigate the regulatory landscape and implement effective recycling programs.
In conclusion, addressing these challenges requires a broad approach. This includes creating financial incentives to make recycling more economically attractive, streamlining logistical processes to reduce costs and improve efficiency, raising awareness and providing education about recycling options, and fostering collaboration among stakeholders to develop standardized practices and supportive policies. By overcoming these challenges, the construction industry can move towards a more sustainable and circular economy for EPS and XPS materials, reducing environmental impact and maximizing resource utilization.

5.5. Proposed Recycling Practices

The provided flowcharts in figures 5.5 and 5.6 illustrate best practices for the sustainable recycling of EPS and XPS waste. These guidelines serve as advice to the industry to adopt the processes and pathways outlined for optimal sustainability.
For EPS, the flowchart in figure 5.5 emphasizes initial assessment based on the material's origin (demolition or unused leftover) and construction date (pre- or post-2016). EPS from structures built before 2016 likely contains hexabromocyclododecane (HBCD), a hazardous flame retardant. If HBCD is present, the EPS should be shredded, separated, compacted, and processed via a dissolution-based recycling method at PS Loop as adviced in section 5.2.
EPS identified as HBCD-free is further evaluated for contamination by substances like bitumen or cement. Contaminated EPS with glue and mortar follows a similar path of shredding, separation, and compaction, with end-uses tailored to the specific contaminant, such as mechanical recycling described in section 5.2. Contaminated material with bitumen can not yet be incorporation into asphalt and has to be incinerated.
Unused EPS should be assessed for potential take-back by the producer. If not reclaimed, it should be directed to EPSolutly collection points for shredding, compaction, and subsequent mechanical recycling. This approach ensures EPS is repurposed instead of incinerated, fostering a circular economy by reincorporating used EPS into new applications or recycling it into fresh polystyrene material.

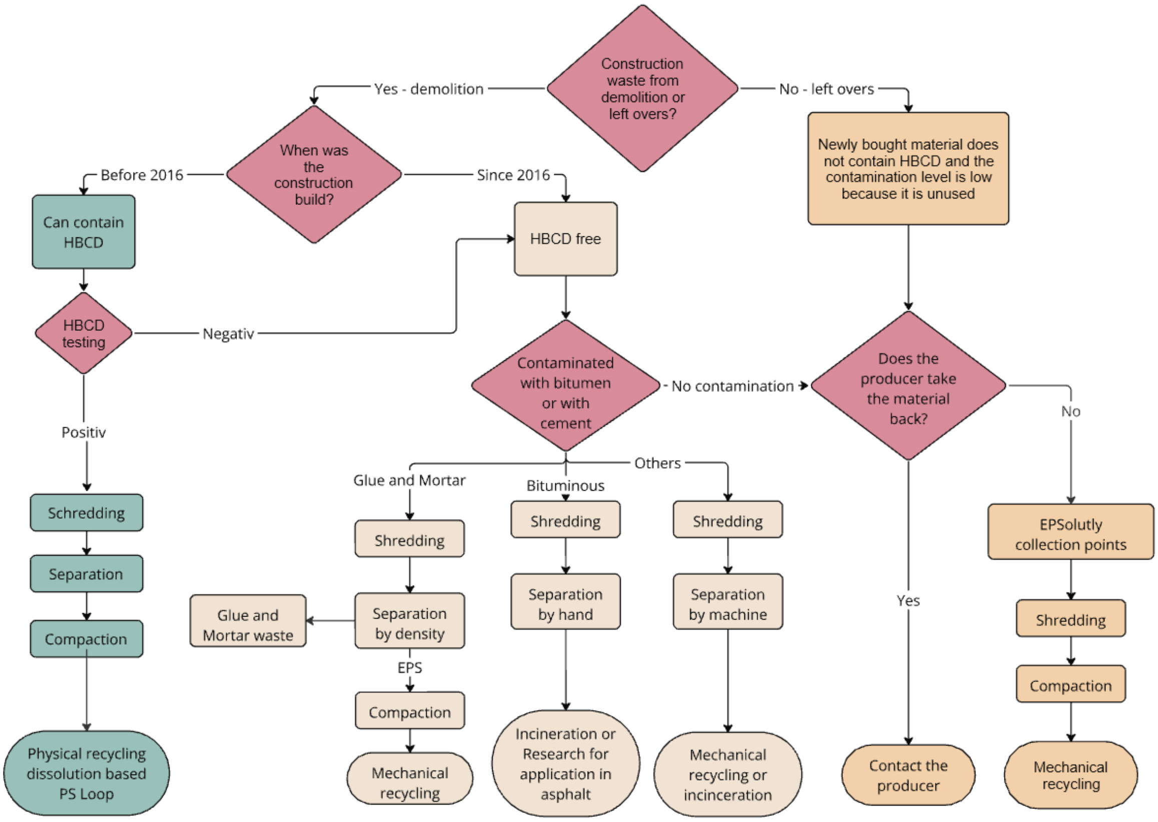


Figure 5.5: Proposed flowchart EPS

For XPS, the flowchart 5.6 outlines a more constrained recycling process, especially for highly contaminated material. XPS from constructions built before 2016 is likely to contain HBCD. This material should undergo degassing to remove chlorofluorocarbons (CFCs), followed by shredding, separation, compaction, and potential solvent-based recycling.
If XPS is HBCD-free, it is evaluated for contamination levels. Highly contaminated XPS should proceed directly to incineration due to the difficulties in cleaning and recycling. Low-contamination XPS, however, can either be taken back by the producer or degassed from CFCs, then shredded, separated, and mechanically recycled. This process highlights the limited recycling options for XPS, especially for contaminated materials, and underscores the reliance on incineration compared to the more versatile recycling pathways available for EPS.
By following these flowcharts, the industry can adopt more sustainable practices in handling EPS and XPS waste, reducing environmental impact and promoting material circularity.

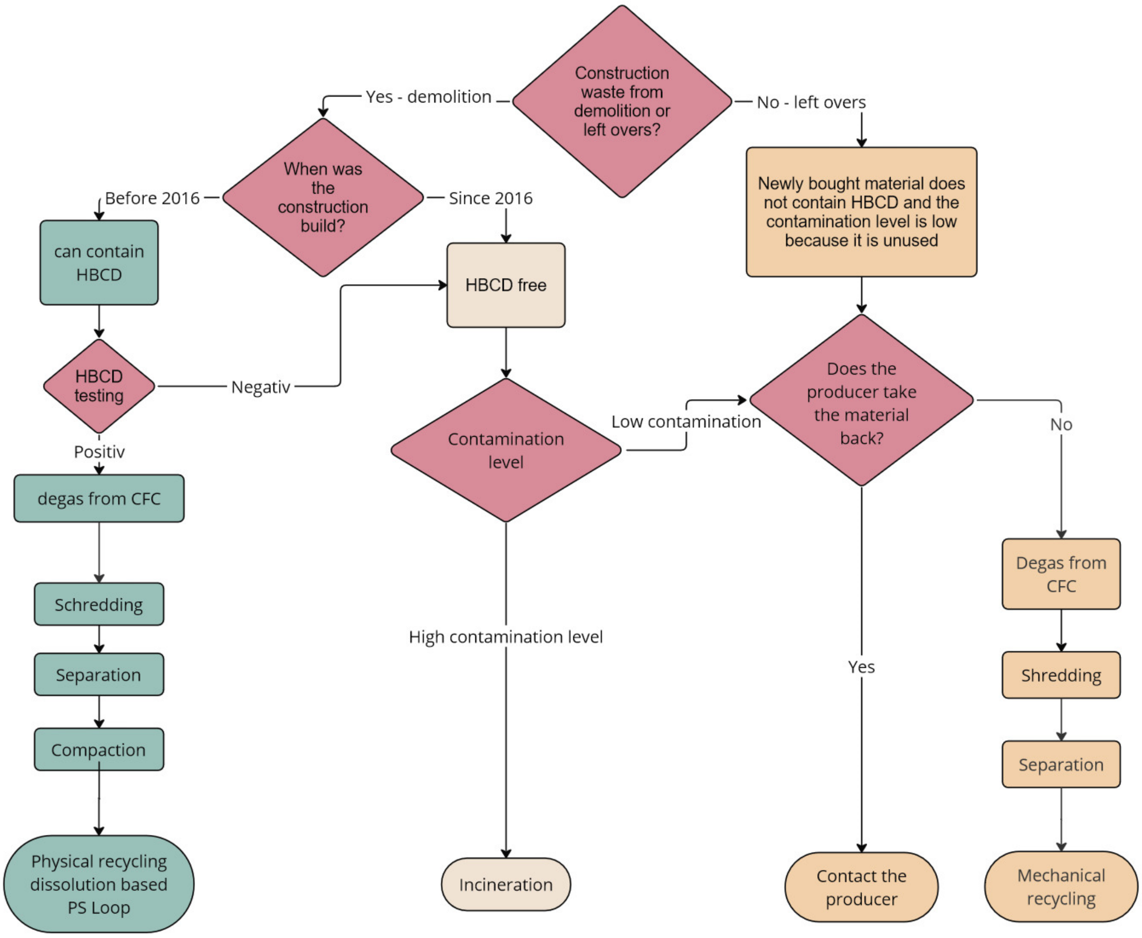


Figure 5.6: Proposed flowchart XPS

6
Environmental and Economic Analyses

The end-of-life management of EPS and XPS presents significant environmental challenges, especially when the waste is contaminated. This Life Cycle Assessment (LCA) aims to evaluate and compare the environmental impacts and economic feasibility of different end-of-life management processes for EPS and XPS, focusing on material that is 10% contaminated with glue and mortar. This specific contamination level represents the type of waste that is currently recyclable but not yet widely processed. In this case study, three processes — mechanical recycling, solvent-based recycling, and incineration — are assessed under various environmental impact categories. The study aims to provide a clear comparison to identify the most sustainable and economically viable solution for managing the end-of-life phase of EPS and XPS materials.

6.1. Environmental Assessment - LCA

The primary goal of this study is to demonstrate that recycling EPS and XPS waste, even with 10% contamination of glue and mortar, is both feasible and beneficial. By focusing on this contamination level, we inherently consider waste streams that are less contaminated and easier to recycle, which do not require separate consideration. Bituminous contaminated materials are excluded from this study as they are currently considered non-recyclable, as demonstrated in before in chapter 4.

This LCA considers three main processes: mechanical recycling, solvent-based recycling, and incineration. Each process has unique environmental impacts and economic implications. By modeling all sub processes within a detailed system, this study provides a comprehensive comparison, aiming to identify the most sustainable and cost-effective solution for EPS and XPS waste management.

The methodology for this LCA is based on the ISO 14040 [76] and ISO 14044 [77] standards, which provide a detailed guide on performing an LCA and the necessary steps involved. These standards ensure that the assessment is thorough, consistent, and aligned with international best practices.

The motivation for conducting this LCA stems from the increasing need to manage EPS and XPS waste more sustainably. With rising environmental regulations and societal pressure to reduce waste and promote recycling, it is crucial to understand the full life cycle impacts of these materials. This chapter aims to inform stakeholders about the most effective strategies for managing EPS and XPS waste, ultimately contributing to more sustainable practices and reduced environmental footprints.

6.1.1. Goal and Scope Definition

The primary objective of this Life Cycle Assessment (LCA) is to identify the most environmentally sustainable and economically viable end-of-life scenarios for EPS and XPS, and to evaluate the environmental impacts and economic feasibility of various proposed solutions for the disposal and recycling of these materials.

This LCA compares three different processes for the end-of-life management of EPS and XPS: mechanical recycling, solvent-based recycling, and incineration. The scope includes modeling all sub processes within the ISO Standards [76] and [77], enabling a detailed comparison of the impact as-

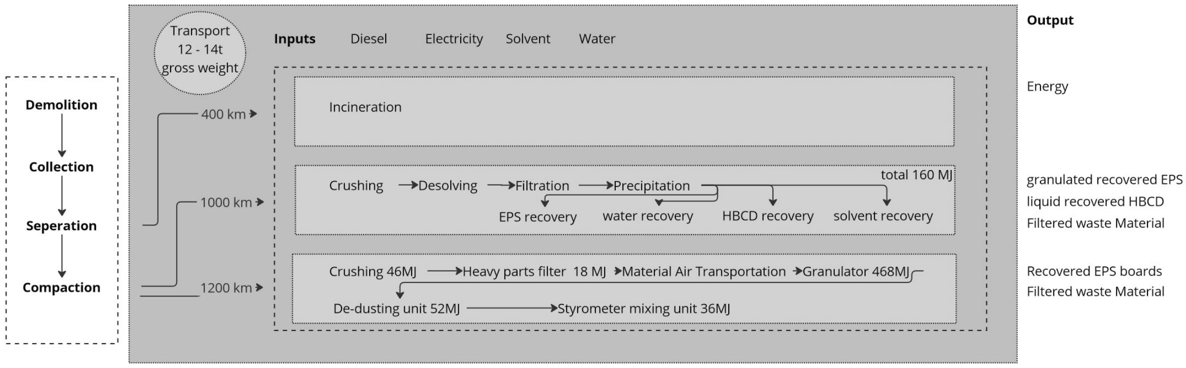


Figure 6.1: System boundary

sessment ReCiPe 2016.
The functional unit for this study is defined as the processing of one tonne of EPS and XPS waste contaminated with 10% glue and mortar. This unit serves as the basis for all data collection and impact assessment. The focus is on the environmental impact of the end of life scenarios processes rather than the EPS production. Including the environmental impact of one tonne of contaminated EPS with glue and mortar in the life cycle inventory could be misleading due to its high environmental impact in the production.
The system boundaries extend from the point of waste collection (gate) to the final disposal or recycling process (grave) as depicted in figure 6.1. This includes the transportation of waste materials, preprocessing steps such as crushing and de-dusting, and the final recycling or disposal stages.
The energy and material inputs and outputs for each process are detailed in the system boundaries diagram. Inputs include diesel, electricity, solvents, and water, while outputs include energy, granulated recovered EPS, liquid recovered HBCD, recovered EPS boards, and filtered waste material.
The impact assessment method used in this study is ReCiPe, which encompasses all relevant impact categories. This comprehensive approach ensures that all potential environmental impacts are considered.
A midpoint analysis is employed, which is robust and suitable for scientific purposes. By focusing on the midpoint indicators, the study provides actionable insights into the environmental impacts associated with each process. This analysis helps to understand the cause-and-effect relationships within the life cycle of the materials.

6.1.2. Life Cycle Inventory - LCI

The Life Cycle Inventory (LCI) details the inputs, outputs, and processes involved in different recycling and disposal methods for EPS. This inventory includes data from both foreground and background processes, focusing on attributional flows. The following sections outline the processes and associated data quality assessments.
Data was collected from primary and secondary sources to ensure comprehensive coverage of the processes involved. Primary data was obtained through direct engagement with industry representatives, while secondary data was sourced from established databases such as Ecoinvent and literature specific to the case study.
The accompanying tables 6.1 - 6.3 provide a detailed breakdown of the data used in the LCI. Each table outlines the specific processes (both foreground and background), the year and geographic location of the data, and the source from which the data was obtained. For instance, the mechanical recycling table 6.1 details processes like truck transport, EPS crushing, filtering, and granulation, along with the associated energy inputs (diesel, electricity). The solvent-based recycling table 6.2 includes information on the solvent recycling process, specific solvents used, and outputs like granulated EPS and recovered HBCD. Finally, the incineration table 6.3 outlines the incineration process, energy inputs, and the resulting electricity output.

Foreground data	Background process	Year	Geo	Source
Mechanical recycling				
Truck transport	Euro 3, 12 - 14t gross weight / 9.3t payload capacity	2022	Global	Ecoinvent
EPS crushing	Grain size 25-100 mm	2024	DK	KBM
Heavy parts filter	capacity 40 m^3/h; filtersize: 7- 5 mm	2024	DK	KBM
Granulator version D	6-10 mm screen	2024	DK	KBM
De-dusting unit	10 - 2.5 μm	2024	DK	KBM
Styrometer mixing system	recycling ratios vary	2024	DK	KBM
Diesel	from crude oil and bio components/ production mix, at refinery	2022	EU28	Ecoinvent
Electricity	AC, technology mix/ consumption mix, to consumer	2022	DK	Ecoinvent
Output				
Recycled EPS				
Filtered waste	production mix (region specific sites), at landfill site	2022	EU28	Ecoinvent
Dust	2.5-10PM	2024	EU18	KBM

Table 6.1: LCI mechanical recycling

Foreground data	Background process	Year	Geo	Source
Solvent based recycling				
Truck transport	Euro 3, 12 - 14t gross weight / 9.3t payload capacity	2024	Global	Ecoinvent
Solvent recycling process	different processes combined	EU28	2024	PS loop
Diesel	from crude oil and bio components/ production mix, at refinery	2022	EU28	Ecoinvent
Electricity	AC, technology mix/ consumption mix, to consumer	2022	NL	Ecoinvent
Tap water from ground water	production mix, at plant	2022	EU28	Ecoinvent
Solvent		2024	NL	PS loop
Ethanol	hydrogenation with nitric acid	2022	EU28	Ecoinvent
Methanol	catalytic reaction of methanol and carbon monoxide	2022	EU28	Ecoinvent
Cyclohexane	catalytic hydration of benzene	2022	EU28	Ecoinvent
Output				
Granulated recycled EPS		2024	EU28	PS loop
Commercial waste	production mix (region specific sites), at landfill site	2022	NL	Ecoinvent
Recovered HBCD		2024	EU28	PS loop

Table 6.2: LCI solvent-based recycling

Foreground data	Background process	Year	Geo	Source
Incineration				
Truck transport	Euro 3, 12 - 14t gross weight / 9.3t payload capacity	2024	Global	Ecoinvent
Polystyrene incineration	production mix (region specific plants), at plant	2022	EU28	Ecoinvent
Diesel	from crude oil and bio components/ production mix, at refinery	2022	EU28	Ecoinvent
Output				
Electricity	consumption mix	2022	Global	Ecoinvent

Table 6.3: LCI incineration

This LCI provides a detailed overview of the processes involved in the end-of-life scenarios for EPS, including mechanical recycling, solvent-based recycling, and incineration. By using data from both industry and the Ecoinvent database, the LCI ensures a reliable foundation for evaluating the environmental impacts of each process.

6.1.3. Life Cycle Impact Assessment - LCIA

A life cycle impact assessment (LCIA) was conducted to evaluate the environmental performance of the three waste treatment processes: mechanical recycling, solvent-based recycling, and incineration. The assessment employed the ReCiPe 2016 v1.1 Midpoint (H) methodology within the GABI software environment. This methodological choice was guided by several factors. ReCiPe 2016 offers a comprehensive assessment framework, covering a wide spectrum of environmental impact categories relevant to waste management, such as resource depletion, human toxicity, and climate change. The midpoint approach was favored for its robustness, focusing on quantifiable impacts at intermediate stages of cause-effect chains, thus mitigating the uncertainties associated with predicting long-term consequences. Furthermore, the harmonized nature of ReCiPe ensures consistent and comparable results across impact categories and life cycle stages. The hierarchical perspective (H) provides a comprehensive overview of potential environmental burdens, crucial for balanced decision-making. The well-established nature of ReCiPe, with its widespread use in LCA studies, further reinforces the reliability and credibility of the assessment results.
The assessment results of the total values, summarized in Table 6.4, reveal distinct environmental profiles for each waste treatment process. The detailed analysis of all different processes and the environmental scores of every input parameter can be found in the Appendix A.

Impact category - ReCiPe 2016 v1.1 Midpoint (H)	**Unit**	**Mechanical recycling**	**Solvent-based**	**Incineration**
Climate change, excl. biogenic carbon	kg CO2 eq.	222	415	3.43E+03
Climate change, incl. biogenic carbon	kg CO2 eq.	220	432	3.43E+03
Fine Particulate Matter Formation	kg PM2.5 eq.	0.243	0.232	0.12
Fossil depletion	kg oil eq.	67.1	156	28.3
Freshwater consumption	m3	0.553	0.675	6.46
Freshwater ecotoxicity	kg 1,4-DB eq.	0.0338	0.0623	0.0132
Freshwater eutrophication	kg P eq.	0.00171	0.00236	0.000219
Human toxicity, cancer	kg 1,4-DB eq.	0.0793	0.112	0.024
Human toxicity, non-cancer	kg 1,4-DB eq.	16.8	26.5	6.55
Ionizing radiation	kBq Co-60 eq. to air	0.685	0.45	0.545
Land use	Annual crop eq. y	13.8	7.84	3.56
Marine ecotoxicity	kg 1,4-DB eq.	0.104	0.182	0.0406
Marine Eutrophication	kg N eq.	0.00469	0.00833	0.00138
Metal depletion	kg Cu eq.	0.665	0.562	0.164
Photochemical ozone formation, Ecosystems	kg NOx eq.	1.76	1.6	0.799
Photochemical Ozone Formation, Human Health	kg NOx eq.	1.75	1.59	0.794
Stratospheric Ozone Depletion	kg CFC-11 eq.	5.61E-05	6.09E-05	2.14E-05
Terrestrial acidification	kg SO2 eq.	0.722	0.696	0.429
Terrestrial ecotoxicity	kg 1,4-DB eq.	36.8	46	9.91

Table 6.4: Environmental impact comparison of waste treatment processes (ReCiPe 2016 v1.1 midpoint (H))

Mechanical recycling consistently demonstrates the lowest impact across nearly all environmental indicators. This is attributed to the minimization of new resource consumption and only the use of energy in the process. Solvent-based recycling, while generally outperforming incineration, exhibits a higher environmental burden than mechanical recycling. The use of solvents and additional processing steps contribute to increased impacts in areas such as resource depletion and toxicity due to the fact that currently the solvents cannot be fully recycled. With further technological advancement the full recyclability of the solvent could be achieved and solvent-based recycling could become less resource intensive than currently. Incineration consistently ranks as the least favorable option, with significantly higher impacts across most categories. This is particularly evident in climate change, resource depletion, and

human toxicity, due to the energy-intensive nature of the process and the potential release of harmful pollutants.
Several key observations emerge from the analysis:

- Climate change: Incineration exerts the most substantial impact on climate change as depicted in figure 6.2, primarily due to the release of greenhouse gases. Solvent-based recycling also contributes significantly, but to a lesser extent, while mechanical recycling demonstrates the most favorable outcome.
- Fossil depletion: This category measures the consumption of fossil fuels (oil, natural gas, coal) throughout the waste treatment process, including energy generation, transportation, and any use of fossil-fuel-derived products, depicted in figure 6.3. Incineration and solvent-based recycling have higher scores in this category, indicating greater fossil fuel depletion compared to mechanical recycling.
- Human toxicity: Incineration poses the greatest risk to human health due to the potential release of toxic substances as depicted in figure 6.4, including heavy metals and particulate matter. Solvent-based recycling also shows a higher impact than mechanical recycling in this category.

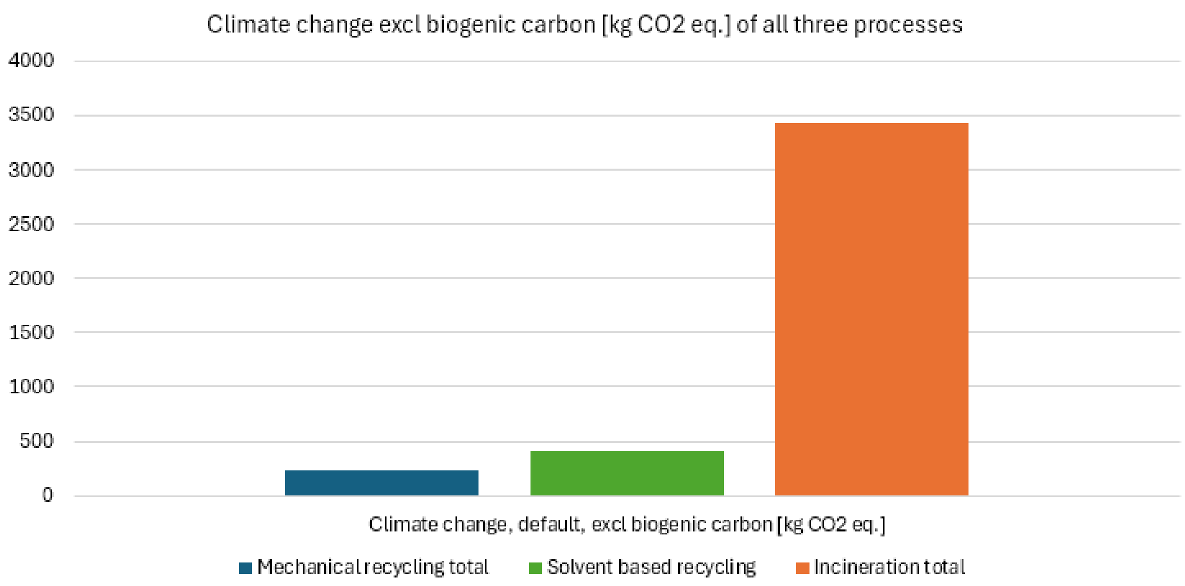


Figure 6.2: Climate change all three processes

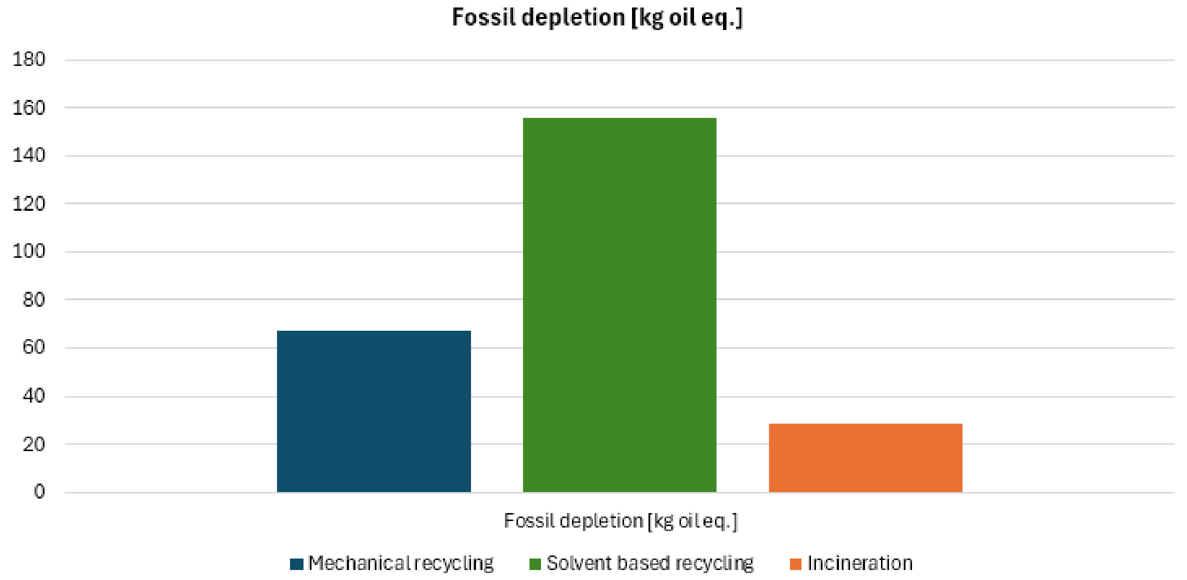


Figure 6.3: Fossil depletion all three processes

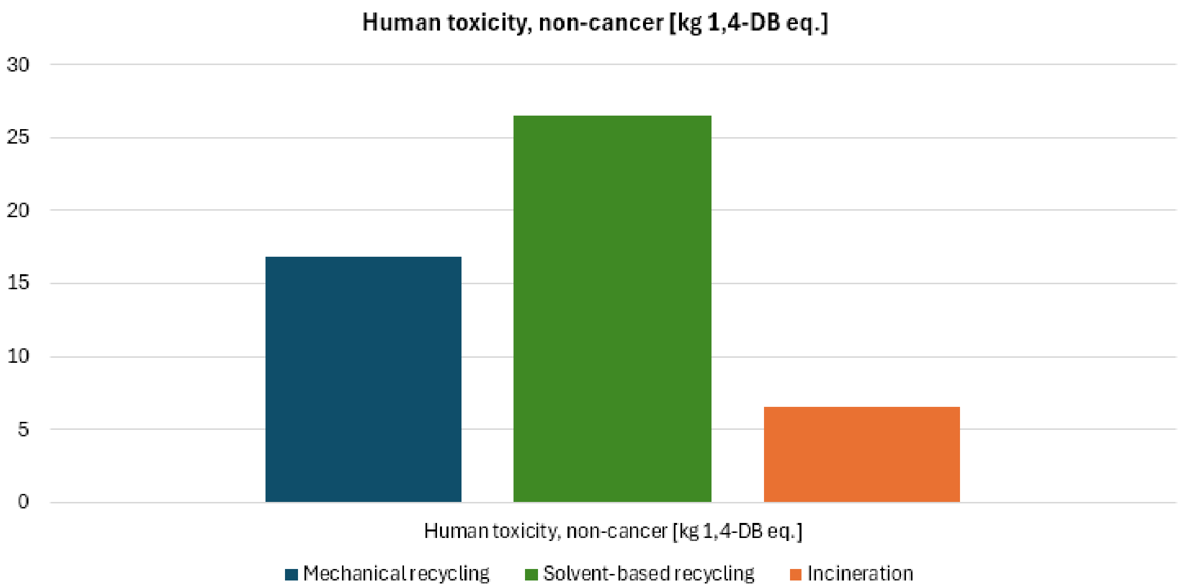


Figure 6.4: Human toxicity non-cancer all three processes

The LCIA underscores the environmental advantages of mechanical recycling over solvent-based recycling and incineration across a wide range of impact categories. While solvent-based recycling may offer benefits in specific cases, mechanical recycling emerges as the most sustainable option for minimizing the overall environmental burden of waste treatment.

Recycling/disposal method	Capacity [m^3/hour]	Mass processed [kg/hour]	Electrical load [kW]	Energy consumption [kWh/kg]
Solvent-based recycling	2.75	500-550	154.28	-0.30
Mechanical recycling	10-12	2000-2400	50.62	-0.023
Incineration	15-20	300-600	1000-1500	+1.683[1]

Table 6.5: Energy consumption and production for different EPS recycling/disposal methods. Red values indicate net energy consumption, and green values indicate net energy production.

Energy analysis suggests solvent-based recycling may be the most efficient in energy consumption per kilogram of EPS, though this data is based on initial assumptions from the recycling plant and requires further validation as the plant has not been operational long enough to confirm these figures. Mechanical recycling follows, becoming more efficient with larger volumes. While incineration uniquely generates net energy, it comes at a higher environmental cost. A comprehensive assessment considering all environmental impacts remains essential for selecting the most sustainable EPS waste treatment method.

6.1.4. Interpretation

The Life Cycle Impact Assessment (LCIA) using the ReCiPe 2016 v1.1 Midpoint (H) methodology reveals distinct environmental profiles for the three waste treatment processes. Mechanical recycling consistently demonstrates the lowest impact across all categories, primarily due to the avoidance of energy-intensive processes and new material production. Its main burdens originate from transportation, particularly the use of less fuel-efficient vehicles, and electricity consumption as seen in figure A.1, figure A.2 and figure A.3, highlighting the potential for significant improvements by transitioning to greener alternatives and possibly relocating recycling plants closer to waste sources. Solvent-based recycling, while enabling resource recovery, exhibits a higher environmental burden due to solvent production and use, along with energy consumption and transportation. Optimizing solvent recovery and transitioning to renewable energy could mitigate these impacts. Incineration consistently ranks as the least favorable option, primarily due to the substantial release of greenhouse gases and pollutants during combustion, outweighing the benefits of energy recovery. To gain a deeper understanding of these results and explore potential improvements, a sensitivity analysis was conducted to assess the influence of key parameters on the overall environmental impact of each process.

Sensitivity Analysis

The sensitivity analysis reveals key opportunities for enhancing the environmental sustainability of EPS and XPS waste management processes:

Mechanical recycling:

- **Truck transport:** The most significant impact reduction potential lies in transitioning from a Euro 3 truck (137.5 kg CO_2 eq.) to a more fuel-efficient Euro 5 truck (10.2 kg CO_2 eq.), leading to a substantial decrease in climate change and resource depletion impacts.
- **Electricity mix:** Shifting from the current electricity mix to 100% wind power would further decrease the climate change impact of mechanical recycling from 54.1 kg CO_2 eq. to 1.77 kg CO_2 eq.

Solvent-based recycling:

- **Solvent production and use:** The most impactful change would be to explore and adopt alternative solvents with lower environmental burdens than the current solvent, which contributes 150 kg CO_2 eq. to climate change. Maximizing solvent recovery and reuse can also significantly reduce the environmental impact of this process.
- **Energy consumption and transportation:** Transitioning to renewable energy sources and using more fuel-efficient trucks for transportation (Euro 3 truck contributing 115 kg CO_2 eq.) is reducing the environmental burden of solvent-based recycling.

Incineration:

[1] Net energy production per 1 kg of EPS incinerated (energy produced minus energy consumed).

- **Inherent environmental challenges:** The dominant environmental impact of incineration stems from the incineration process itself (3.37E+03 kg CO_2 eq.), making it the least sustainable option. While improvements in energy recovery efficiency and flue gas treatment can offer some mitigation, the inherent nature of incineration presents significant environmental challenges that cannot be fully overcome.
- **Marginal improvements:** Optimizing transportation (52.3 kg CO_2 eq. from Euro 3 truck) and energy use (8.82 kg CO_2 eq.) can lead to marginal reductions in the overall environmental impact.

The sensitivity analysis underscores the importance of optimizing transportation and energy sources in mechanical and solvent-based recycling. It also emphasizes the need to explore alternative solvents and maximize solvent recovery in solvent-based recycling. While improvements are possible for incineration, its inherent environmental burden remains a major concern, reinforcing its position as the least preferred option for EPS and XPS waste management.

6.1.5. Conclusion

The LCIA and sensitivity analysis reaffirm the environmental superiority of mechanical recycling as the most sustainable solution for EPS and XPS waste management. It scores the lowest environmental burden across most impact categories, mainly due to avoiding energy-intensive processes and minimizing new resource consumption.

Solvent-based recycling, while enabling resource recovery, presents a more complex environmental profile. Its sustainability depends on the choice of solvent, the efficiency of solvent recovery and reuse, and the source of energy used. Prioritizing less harmful solvents, maximizing solvent recycling, and transitioning to renewable energy sources are crucial steps to enhance its environmental performance.

Incineration, despite its energy recovery potential, remains the least desirable option due to its significant environmental impacts, particularly in climate change and resource depletion. While advancements in energy recovery and pollution control may offer marginal improvements, the inherent nature of the process poses environmental challenges.

In conclusion, this study strongly advocates for prioritizing mechanical recycling as the primary strategy for managing EPS and XPS waste. When mechanical recycling is not feasible, solvent-based recycling presents a viable alternative, provided that conscious efforts are made to minimize its environmental footprint through solvent selection, energy sources, and process optimization. Incineration, though capable of energy recovery, should be considered a last resort due to its high environmental burden.

6.2. Economic Assessment

This economic assessment complements the preceding LCA by evaluating the economic sustainability of the same three end-of-life processes for EPS and XPS: mechanical recycling, solvent-based recycling, and incineration. The primary goal is to assess the life cycle costs associated with managing one tonne of EPS and XPS waste contaminated with 10% glue and mortar, mirroring the waste stream analyzed in the LCA.

The scope encompasses three distinct life cycle stages: end-of-life transportation, end-of-life processing, and end-of-life use (potential revenues from recovered materials or energy).

6.2.1. Life Cycle Cost Analysis - LCCA

This economic assessment analyzes the cost-effectiveness of various management strategies for EPS and XPS waste contaminated with 10% glue and mortar. The study focuses on three end-of-life processes: mechanical recycling, solvent-based recycling, and incineration.

To facilitate a comprehensive comparison, the analysis considers two distinct scenarios for incineration: one without HBCD and one with HBCD. This allows for a direct comparison between mechanical recycling and a typical incineration process for non-hazardous waste, and between solvent-based recycling (which is primarily used for HBCD-containing materials) and a process designed for hazardous waste.

The analysis is based on a functional unit of 1 m³ of contaminated material. The costs are categorized into transportation, processing, and potential revenues.

Methodology and assumptions:

- Mechanical recycling: Cost estimations are derived from data provided by KBM recycling machines. These machines are renowned for their high standards and have provided detailed technical and economic information for the calculations.

- Incineration: Cost estimations are based on standard prices for incineration in various countries (Austria, Germany, Netherlands, Belgium). A gross margin of 25% has been deducted as only the customer's cost is known. The costs encompass the entire process: shredding, combustion, flue gas cleaning, and residue management.
- Solvent-based recycling: Cost estimations are based on information gathered during site visits and discussions with professionals in the solvent-based recycling industry. In this estimation, a recycling rate of 90% for the solvent has been assumed.
- Transportation: Standard assumptions are employed for truck size, time, and distance, considering typical industry practices.

Tables 6.6, 6.7, 6.8, and 6.9 provide a detailed breakdown of the costs for each process.
It is important to note that this analysis solely focuses on direct costs associated with waste management. It does not consider indirect costs or benefits, such as potential subsidies, environmental impacts (which were quantified in the LCA), or fluctuating market prices for recycled materials or energy. The variability in disposal costs (e.g., landfill fees for recycling residuals and ash disposal for incineration) and potential revenues (from recycled materials or energy generation) are acknowledged but not explicitly quantified in these tables.
Table 6.10 summarizes the costs for each process, highlighting the significant differences in processing costs.

Category	**Unit**	**Value**	**Cost (€/m3)**
Transportation			
Truck capacity	t	25	
Truck capacity	m³	$\sim$ 50	
Transport distance	km	1200	
Transport time	h	19	
Truck running costs	€/km	0.375	
Average wage of truck driver	€/h	50	
Total truck costs	€/(19h)		1,400.00 (19h)
	€/m³		19.14
Diesel for loaded truck	l/km	0.3	
Diesel costs	€/l	1.85	
Total diesel cost	€/(19h)		666.00 (19h)
	€/m³		13.32
Total transportation cost	€/h	$\sim$ 85	**2,066 (19h)**
	€/m³		**41.32**
Recycling			
Density of material	kg/m³	20	
Electricity	kWh/kg	0.023	
Electricity price	€/kWh	0.15	
	€/m³		0.07
Machinery acquisition cost	€	200,000	
Machinery time	years	15	
Machinery depreciation	€/year	13,333	
Machinery use	m³/h	12	
Machinery use	m³/year	$\sim$ 25,000	
Machinery depreciation	€/m³		0.53
Average wage technician	€/h	70	
	€/m³		5.83
Total recycling cost	€/m³		**6.43**
Total cost (Per m³)	€/m³		**47.75**

Table 6.6: Cost breakdown for mechanical recycling

Category	Unit	Value	Cost (€/t)
Transportation			
Truck capacity	t	25	
Truck capacity	m³	$\sim$ 50	
Transport distance	km	500	
Transport time	h	7	
Truck running costs	€/km	0.375	
Average wage of truck driver	€/h	50	
Total truck costs	€/(7h)		537.5 (7h)
	€/m³		10.75
Diesel for loaded truck	l/km	0.3	
Diesel costs	€/l	1.85	
Total diesel cost	€/(7h)		277.5(7h)
	€/m³		5.55
Total transportation cost	€/h	$\sim$ 85	**815 (7h)**
	€/m³		**16.3**
Incineration costs			
Austria	€/t	375	
Density insulation	kg/m³	20	
Density mortar	kg/m³	2000	
5% contamination of mortar	kg/m³	119	
	€/m³		44,6
Total cost Austria (per m³)	€/m³		**60.9**

Table 6.7: Cost breakdown of incineration for polystyrene without HBCD

Category	Unit	Value	Cost (€/to)
Transportation			
Truck capacity	t	25	
Truck capacity	m³	$\sim$ 50	
Transport distance	km	1000	
Transport time	h	15	
Truck running costs	€/km	0.375	
Average wage of truck driver	€/h	50	
Total truck costs	€/(15h)		1,125.00 (15h)
	€/m³		22.5
Diesel for loaded truck	l/km	0.3	
Diesel costs	€/l	1.85	
Total diesel cost	€/(15h)		555.00 (15h)
	€/m³		11.1
Total transportation cost	€/h	$\sim$ 85	**1,680 (15h)**
	€/m³		**33.6**
Recycling			
Density of material	kg/m³	200	
Recycling rate	h/t	2	
Electricity	kWh/kg	0.3	
Electricity price	€/kWh	0.15	
	€/m³		0.66
Tap water from ground water excl. recovery	m³/h	0.25	
recovery rate	%	60	
Water price	€/m³	1.7	
	€/m³		0.34
Solvent consumption excl. recovery	m³/t	6.81	
Recovery rate	%	90	
Solvent	€/m³	6360.00	
	€/m³		636.00
Machinery acquisition cost	€	1,000,000	
Machinery time	years	20	
Machinery depreciation	€/year	50,000	
Machinery use (h)	m³/h	0.4	
Machinery use (year)	m³/year	18,430	
Machinery depreciation	€/m³		2.71
Average wage technician	€/h	70	
Number of technicians		5	
	€/m³		140
Total recycling cost	€/m³		**779.4**
Total cost (Per m³)	€/m³		**813.00**

Table 6.8: Cost breakdown for solvent-based recycling

Category	Unit	Value	Cost (€/t)
Transportation			
Truck capacity	t	25	
Truck capacity	m³	~ 50	
Transport distance	km	500	
Transport time	h	7	
Truck running costs	€/km	0.375	
Average wage of truck driver	€/h	50	
Total truck costs	€/(7h)		537.5(7h)
	€/m³		10.75
Diesel for loaded truck	l/km	0.3	
Diesel costs	€/l	1.85	
Total diesel cost	€/(7h)		277.5(7h)
	€/m³		5.55
Total transportation cost	€/h	~ 85	**815 (7h)**
	€/m³		**16.3**
Incineration costs			
Austria	€/t	2,625	
Density insulation	kg/m³	20	
Density mortar	kg/m³	2000	
10% contamination of mortar	kg/m³	218	
	€/m³		572.25
Germany	€/t		500 - 8000
Netherlands	€/t		700
Belgium	€/t		350
Total cost Austria (Per m³)	€/m³		**588.55**

Table 6.9: Cost breakdown of incineration for polystyrene containing HBCD

Category	Unit	Mechanical recycling	Incineration without HBCD	Solvent-based recycling	Incineration with HBCD
Transportation					
Transport distance	km	1200	500	1000	500
Total transportation cost	€/m³	41.32	16.3	33.6	16.3
Processing					
Total processing cost	€/m³	6.36	44.6	572	1109.5
Total cost	€/m³	**47.75**	**60.9**	**813.00**	**588.55**

Table 6.10: Comparison of cost for different waste processing options

Interpretation

The cost breakdowns presented in tables 6.6, 6.7, 6.8, and 6.9 reveal that mechanical recycling and incineration without HBCD are in a similar cost range, as are solvent-based recycling and incineration with HBCD. This suggests that, at least from a purely financial perspective, the current practice of incineration is not necessarily less attractive than recycling for EPS and XPS waste.
Table 6.10, further emphasizes this point. It demonstrates that the total cost of incineration (both with and without HBCD) is comparable to the costs of mechanical and solvent-based recycling. This finding challenges the common assumption that recycling is inherently more expensive than incineration.

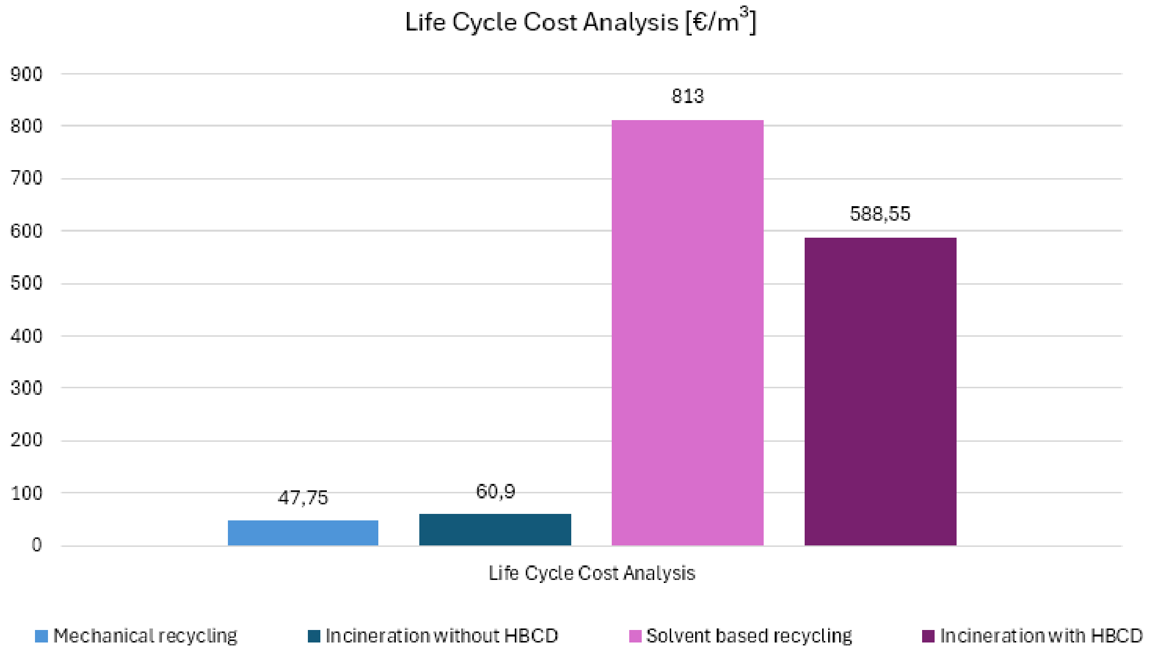


Figure 6.5: LCCA comparison

However, it is important to consider the context. While incineration currently appears financially comparable, recycling often requires more effort and investment upfront. Mechanical and solvent-based recycling require a larger volume of material to achieve lower operating costs. While offering the potential for higher value recovery, both options necessitate significant investment in logistics and a shift away from current practices.
Furthermore, the current infrastructure for recycling EPS and XPS is limited, and few companies currently offer these services. This lack of widespread adoption contributes to a perception of higher costs for recycling compared to the established practice of incineration.
A significant factor influencing this situation is that incineration companies operate as a business model based on waste disposal. This creates a financial incentive for incineration, as they receive revenue from waste disposal, even if the material could be recycled. This is particularly true for municipal or government-run incinerators further incentivize incineration over recycling.
The cost breakdowns in the tables reveal some interesting findings. Mechanical recycling emerges as the most cost-effective option, with a total cost of 47.75 €/m³, placing it in a similar range as non-HBCD incineration (60.9 €/m³). This demonstrates that, even with higher transportation costs associated with longer distances, mechanical recycling can be financially competitive with traditional incineration methods. Solvent-based recycling, on the other hand, stands out as the most expensive option (813.00 €/m³) due to the high price of solvents (6360.00 €/m³), despite a 90% recovery rate. This highlights the critical role of efficient solvent management and recovery in ensuring the economic feasibility of this recycling method. Notably, the cost of incineration for HBCD-containing materials, while generally higher (588.55 €/m³) due to the management of hazardous waste, can vary significantly based on location. In countries like Belgium, where the cost is 350 €/t, it can be cheaper, demonstrating the influence of regional regulations and infrastructure on costs.
In summary, while the initial costs of recycling EPS and XPS waste may seem comparable to incineration, the lack of widespread recycling infrastructure and the inherent business model of incineration companies create barriers for wider adoption of more sustainable waste management practices. This highlights the need for increased investment in recycling infrastructure and a shift in priorities away from purely financial considerations to encompass broader environmental and circular economy goals. Further analysis, including a Circular Economy Index (CEI) evaluation, will be conducted to provide a more nuanced understanding of the economic viability and circularity of each waste management approach.

6.2.2. Circular Economy Index - CEI

The Circular Economy Index (CEI) is a metric used to assess the effectiveness of recycling processes in recovering the inherent value of materials. A higher CEI indicates a greater degree of circularity, as it signifies a larger proportion of the input material's value being recovered through recycling [78].
This analysis focuses on the economic value of material recovery, providing a simple measure of circularity by quantifying the value generated from waste materials. The CEI is calculated as:

$$CEI = \frac{\text{Market value of recycled materials}}{\text{Market value of input materials}} \tag{6.1}$$

To calculate the CEI as seen in table 6.11 accurately, the following market values are required:

- Market value of contaminated EPS and XPS (input material): The cost per tonne of the waste material before processing.
- Market value of recycled EPS: The price per tonne at which recycled EPS can be sold.
- Market value of recovered HBCD (solvent-based recycling): The price per unit of recovered HBCD.
- Market value of energy (incineration): The revenue generated per tonne of EPS and XPS incinerated through energy recovery.

Item	Mechanical recycling (value)	Solvent-based recycling (value)	Incineration (value)
Market value of input material(€/m³)	**80**	**80**	**80**
Market value of recycled EPS (€/m³)	**64**	**72**	-
Market value of recovered HBCD (€/unit)	-	**unknown**	-
Market value of energy (€/m³)	-	-	**8.48**
CEI	**0.8**	**0.9**	**0.11**

Table 6.11: Data requirements for CEI calculation and resulting CEI values

Interpretation

A higher CEI indicates a greater degree of circularity, as it signifies a larger proportion of the input material's value being recovered through recycling or energy generation. In this case, solvent-based recycling exhibits the highest CEI (0.9), followed by mechanical recycling (0.8), and lastly, incineration (0.11). This suggests that solvent-based recycling is the most effective method for recovering the economic value of EPS, while incineration is the least effective.
The CEI values in the table reflect the varying degrees of value recovery associated with each method. In mechanical recycling, the recycled EPS is valued around 64 €/m³ (recycling facility data), indicating a loss of value compared to the initial 80 €/m³ (the market usual price in Austria). This is because the mechanical recycling process does not fully restore the EPS to its original quality, requiring the addition of virgin material to produce usable insulation boards.
Solvent-based recycling, on the other hand, yields a higher value of 72 €/m³ (around 90% of initial price was indicated by the recycling facility) for the recycled EPS, as it produces a higher quality product comparable to virgin EPS. However, the value of the recovered HBCD is unknown, which could potentially increase the CEI further if it has a significant market value.
Incineration, while not a recycling process, generates some value through energy recovery, with a market value of 8.48 €/m³ (this is based on the density the calorific value of 10,6 kWh/kg, 40% efficiency of the incineration power plant recovery rate of energy and 0,01€/kWh common selling prices of energy). However, this is significantly lower than the value recovered through recycling methods, resulting in the lowest CEI of 0.11.

Limitations

It is important to note that the CEI has limitations. It focuses on the economic value of material recovery and does not consider other important aspects of circularity, such as energy efficiency, pollution

prevention, and overall environmental impact. Therefore, it should not be used as the sole indicator of a process's circularity, but rather as a complementary metric alongside other assessments.
For instance, while recycling has a higher CEI when just looking at the recovered value, it is important to consider that these process use more resources as well as it can be repeated a limited number of times due to the degradation of the chemical composition of the EPS. Additionally, the environmental impact of the solvents used in the process needs to be evaluated. Incineration, despite having the lowest CEI, might be a preferable option in certain situations where energy recovery is a priority, and the environmental impact can be mitigated through proper emission controls.
Therefore, a comprehensive assessment of the circularity of EPS disposal methods should consider not only the economic value recovered (as indicated by the CEI) but also the environmental and technical aspects of each process.

6.2.3. Weighted CEI

The CEI provides a quantitative measure of how well a process aligns with circular economy principles. A weighted scoring system was developed based on the following principles, incorporating data from the LCA and cost analysis:

1. Material conservation: Evaluates the degree of material reuse (percentage of recycled EPS output) and waste generation.
2. Resource recovery: Assesses the recovery of valuable resources, in this case, HBCD in solvent-based recycling.
3. Energy efficiency: Considers electricity consumption per kilogram of waste processed and the potential use of renewable energy sources.
4. Pollution prevention: Evaluates the overall environmental impacts across various categories identified in the LCA.
5. Material use: Measures the amount of extra material, such as solvents, that are being used in the process.

The Environmental impact score ranges from 0 to 100, reflecting the sustainability performance of a product or process. A score of 0 indicates the worst possible environmental outcome, with no recycling or resource recovery, while a score of 100 represents the most sustainable scenario with optimal performance, minimal impact, high resource recovery and low costs. Scores between these extremes reflect varying degrees of environmental impact, resource consumption, and recovery. Lower scores indicate higher impacts, consumption, and longer transportation distances, while higher scores signify lower impacts, consumption, and greater resource recovery.

Principle	**Weight (%)**	**Mechanical recycling**	**Solvent-based recycling**	**Incineration**
Material conservation	20	90	85	0
Resource recovery	15	90	100	0
Energy efficiency	15	80	60	20
Pollution prevention	15	95	80	10
Material use	10	100	10	100
Transportation costs	10	50	65	75
Operation costs	15	95	60	55
Overall CEI	100	**87**	**69.5**	**30.25**

Table 6.12: Comparison of weighted CEI for different recycling and disposal methods
The weights assigned to each principle can be adjusted based on specific priorities or stakeholder preferences. The scoring system is transparent and based on measurable data from the LCA and cost analysis. This weighted CEI provides a comprehensive evaluation of the circularity of the three waste treatment processes, considering both environmental and economic aspects.

$$\text{Overall CEI} = (\text{Weight1} \times \text{Score1}) + (\text{Weight2} \times \text{Score2}) + (\text{Weight3} \times \text{Score3}) + (\text{Weight4} \times \text{Score4}) \tag{6.2}$$

Interpretation

- **Mechanical recycling**: High scores for most principles, indicating high efficiency and low environmental impact.
- **Solvent-based recycling**: Excellent resource recovery but higher energy consumption and use of solvents.
- **Incineration**: Scores lowest due to no recycling and high impacts, despite low material use and moderate transportation costs.

The overall CEI is a weighted sum of these principles, reflecting the overall performance of each method. Mechanical Recycling scores the highest, indicating it is the most efficient and environmentally friendly option, followed by Solvent-Based Recycling and then Incineration.

The process with the highest overall CEI is considered the most aligned with circular economy principles. In this case, mechanical recycling scores the highest (87), followed by solvent-based recycling (69.5) and then incineration (30.25). This indicates that mechanical recycling best adheres to circular economy principles among the three processes, primarily due to its high material conservation and low environmental impact. Solvent-based recycling also performs well, mainly due to resource recovery and material conservation, despite its higher energy consumption and solvent use. Incineration scores the lowest due to the absence of material recovery and high environmental impacts.

Limitations

The selection and weighting of principles are subjective and can vary depending on stakeholder priorities. Additionally, the model doesn't account for all possible environmental impacts, and more factors can be added or be excluded according to the user.

6.2.4. Interpretation

The analysis of EPS and XPS waste treatment strategies reveals a trade-off between economic costs, resource recovery, and environmental impact. While mechanical recycling emerges as the most cost-effective and environmentally sustainable option, solvent-based recycling presents a higher economic value recovery due to the quality of recycled EPS produced. However, solvent-based recycling falls behind when considering broader environmental impacts. Incineration, while capable of generating energy, is the least circular option but very cost efficient and therefore also very widely used.

The economic viability of each strategy is sensitive to fluctuations in key variables such as energy prices, solvent costs, and market values for recycled materials, underscoring the need for ongoing monitoring and adaptation to changing conditions.

This analysis highlights the importance of carefully selecting assessment methods, as different approaches can lead to different conclusions about the most favorable waste treatment strategy. While a purely economic assessment might favor incineration, a more comprehensive evaluation that includes environmental impacts reveals solvent-based recycling as the superior option.

The choice of the most suitable strategy depends on specific priorities and the chosen assessment framework. For those prioritizing cost-effectiveness or environmental sustainability, mechanical recycling is the clear choice. However, if the potential revenue from HBCD recovery outweighs the higher environmental costs, solvent-based recycling could be a viable option. Incineration is mostly considered if resouce recovery is not the considered, but its environmental impact should be carefully managed.

6.2.5. Conclusion

The analysis emphasizes the need to evaluating waste management strategies by considering not only economic costs but also resource recovery, environmental impact, and circular economy principles. The findings suggest that mechanical recycling emerges as the most viable option for EPSa and XPS waste management without HBCD, offering the best balance of cost-effectiveness, environmental sustainability, and alignment with circular economy principles. However, the specific needs and priorities of individual stakeholders should be carefully considered when making decisions regarding waste treatment strategies. Exploring ways to improve the economic viability of mechanical recycling and the environmental performance of solvent-based recycling will ultimately promote the development of more sustainable and circular waste management practices for EPS and XPS.

7
Discussion

This section talks about the complexities of EPS and XPS waste management in the construction industry, highlighting the separation between theoretical solutions and practical implementation. The research reveals that while various recycling methods exist, their adoption is hindered by economic, logistical, and material-specific challenges. The study identifies potential solutions, such as sorting and processing, collaboration between stakeholders, and the development of innovative existing technologies. Additionally, the research emphasizes the importance of policy and regulation in incentivizing sustainable practices and promoting a circular economy for EPS and XPS. By addressing these challenges and assessing possibilities, the construction industry could transform EPS and XPS waste from an environmental burden into a valuable resource.

Gap between Theory and Practice

A significant gap exists between the theoretical potential of EPS and XPS recycling, as presented in academic literature, and its practical implementation in the construction industry. While numerous recycling methods exist, including mechanical recycling (grinding and re-granulation) and chemical recycling (dissolution, pyrolysis, catalytic degradation), their adoption is often hindered by economic and logistical constraints [8].

For EPS, while mechanical recycling is promising, the need for densification and contamination issues pose challenges. Chemical recycling methods offer potential solutions for contaminant removal and closed-loop recycling, but their economic viability remains uncertain [57]. For XPS, its higher density make it less suitable for mechanical recycling in literature, while chemical methods, though more appropriate, also face economic and logistical barriers [5]. In practice mechanical recycling can be applied to both EPS and XPS when being prepared properly [6], [5]. Chemical and solvent-based recycling in practice is not yet widely used due to its high economic investment [8].

The literature often overlooks these practical considerations, focusing primarily on technical feasibility. A more comprehensive assessment that considers both technical and economic aspects is needed to guide the industry towards sustainable EPS and XPS waste management.

Practical Hurdels and Potential Solutions

While academic literature provides a theoretical foundation for EPS and XPS recycling, it often overlooks the practical challenges faced by the construction industry. This work bridges that gap by examining real-world case studies and experiences, revealing that while recycling technologies exist, their adoption is limited due to cost, logistics, and lack of awareness.

A key finding is the disconnect between construction companies, who generate the waste, and waste management companies, who are responsible for disposal. This disconnect often leads to missed opportunities for sorting and recycling. To improve recycling rates, construction companies can take proactive steps such as maintaining detailed records of materials used and prioritizing on-site sorting during demolition [8]. Crushing and separation, using machinery like the WEIMA Zerkleinerer [69] and UMS Lufttrennherd [70], can further enhance recycling efficiency by reducing contamination levels to below 10% and minimizing processing and transportation costs. However, due to a lack of incentives,

this is rarely done by waste management companies or construction companies [26].
For smaller volumes of demolition material or material with minimal contamination, on-site processing using machinery like the UMS Lufttrennherd could be sufficient, eliminating the need for further recycling and associated transportation costs. For moderately contaminated materials (up to 5%), the mechanical recycling process could potentially be simplified, warranting further research into streamlined recycling methods. To minimize contamination in the first place, the use of new materials that result in less contaminated EPS and XPS insulation boards is highly recommended. These set of materials eliminate the stabilizing adhesive property and exchange it with fasteners that can be easily removed and reused or recycled. This new approach would highly diminish the contamination level [26].
The research also found that the amount and contamination level of EPS and XPS waste significantly impact the economic feasibility of recycling. Especially processing and purification of EPS and XPS are would be additionally needed, these processes are typically time and resource-intensive. Additionally, despite their higher costs, new materials that minimize contamination on EPS and XPS boards should be used more frequently [8].

The Missing Link

Interviews with stakeholders in the Austrian construction and waste management industries reveal a lack of clear incentives for EPS and XPS recycling. This is due to several factors. Consultancy companies, like EPEA, are skeptical about the economic viability of post-consumer recycling because of high costs and logistical challenges. Additionally, waste management companies, whose income comes from construction companies paying for waste disposal, lack sufficient motivation to invest in recycling infrastructure [8]. This misalignment of incentives hinders the adoption of more sustainable practices.
To overcome these barriers, a shift in the industry's mindset is necessary. Construction companies need to actively demand and support recycling solutions, while waste management companies should be encouraged to explore innovative recycling technologies and business models that prioritize resource recovery over disposal. A key factor in driving this change is the implementation of clearer regulations and incentives for recycling, which could create a more level playing field and encourage the industry to move towards a circular economy [8].
The market outlook for recycled EPS and XPS is promising. There is growing demand for sustainable construction practices in general, and recycled materials are increasingly attractive to consumers and businesses. However, challenges remain. Recycled EPS and XPS materials still compete with cheaper virgin and less sustainable materials, and ongoing innovation in recycling technologies is needed to ensure the quality and consistency of recycled products.
By implementing a combination of incentives such as grants and special taxes, regulations, and ongoing innovation, the construction industry can make significant progress toward a circular economy for EPS and XPS.

Designing for Recyclability

To ground these theoretical considerations in practical realities, this study investigates the specific characteristics of EPS and XPS waste generated in the construction industry. By examining the properties of these materials, their varying levels of contamination, and the consequences for recycling and reuse, this aims to inform targeted strategies for sustainable waste management.
EPS and XPS waste exhibit distinct properties that influence their recycling potential and reuse applications. The low density of EPS and XPS, primarily composed of air, makes it bulky and costly to transport and process. This necessitates volume reduction techniques like compaction before recycling, which can be achieved using specialized equipment such as the "FZ-Recycling compaction tool" or the "EP-STEC Compaction unit." Additionally, the varying levels of contamination in EPS waste, ranging from minimal contamination in fresh offcuts to significant contamination with adhesives, mortar, or bitumen in used insulation, dictate the choice of recycling methods. While uncontaminated EPS can be mechanically recycled, contaminated EPS requires more complex processes like solvent-based recycling (CreaSolv® process) to remove impurities [8]. The choice between mechanical and solvent-based recycling is influenced by the presence of hazardous flame retardants like HBCD, which necessitates specialized treatment to comply with environmental regulations [18].
XPS, with its higher density and closed-cell structure makes it more difficult to break down. The pres-

ence of flame retardants and other additives further complicates recycling for example to remove chlorofluorocarbons (CFCs) from XPS before recycling, as highlighted by PS Loop processes, adds another layer of complexity to the process.
The properties of EPS and XPS waste also influence their potential applications after recycling. Recovered and clean EPS, can be used in non-structural applications like lightweight concrete and void filling. However, its non-biodegradable nature raises concerns about long-term environmental impact. Recovered XPS, has limiting its potential applications before being recycled back into its original material [5].
The analysis of EPS and XPS waste reveals that the characteristics of these materials, particularly their varying levels of contamination, significantly influence their potential for recycling and reuse. The research identifies the main waste streams from a construction company: fresh material from the construction site such as off cuts, EPS and XPS in wall insulation contaminated with glue and mortar, EPS for roof insulation contaminated with bituminous material. These levels of contamination directly impacts the choice of recycling method and the potential applications for the recycled material. Off cuts, uncontaminated EPS and XPS can be easily reintroduced into the production cycle, while contaminated materials require more complex separation and processing techniques. For instance, EPS contaminated with glue and mortar can be mechanically recycled if the contamination level is reduced to below 10%. This is only possible if additionally there is no other contamination from toxic chemicals such as Persistent Organic Polutants (POP). However, EPS contaminated with bitumen currently lacks established recycling methods due to the difficulty of separating the materials [8].
The consequences of these varying waste characteristics are significant for the construction industry. The inability to effectively sort and recycle contaminated EPS and XPS leads to increased waste disposal in incineration or even landfills, both of which have negative environmental impacts. Furthermore, the lack of separation techniques for certain waste streams can increase costs for construction companies, as they must pay for special disposal or invest in expensive separation technologies.
Understanding the characteristics of EPS and XPS waste and their consequences is necessary for developing targeted recycling strategies and promoting the use of more sustainable construction materials. By addressing the challenges posed by contamination, the industry can move towards a more circular economy, where waste is minimized, and resources are reused.

Given these diverse material characteristics and their implications for recycling, a comprehensive understanding of the technical and logistical aspects of EPS and XPS waste processing tailored to the amount of waste is essential. This entails examining the specific technologies and processes required for effective waste management at both on-site and off-site locations, considering the scale of the waste scale, as well as addressing the logistical challenges inherent in implementing these solutions within the dynamic context of construction companies.
To further illustrate the relationship between industry scale and recommended waste management strategies, consider the following table:

Waste stream	Scale	Recommended processes	Advantages	Disadvantages
Fresh EPS and XPS off-cuts	Small	On-site sorting, direct reuse/recycling (EPSolutely)	Low cost, high efficiency	Limited availability of collection points
Glue and mortar contaminated insulation	Small	On-site sorting (WEIMA Zerkleinerer, UMS Lufttrennherd), mechanical recycling	Reduces contamination, cost-effective	Requires investment in machinery
Glue and mortar contaminated insulation	Large	On-site sorting, compacting, specialized mechanical recycling facility	Higher output, Reduced transportation costs	Requires significant investment, complex logistics
Bitumen-contaminated roof insulation	Small	Disposal (current limitations)	None	Limited options, high costs
Bitumen-contaminated roof insulation	Large	Research	Potential for future solutions	Uncertain timeline, requires research funding

Table 7.1: Recommended waste management strategies for EPS and XPS based on scale and waste stream

Waste Management

The effective processing of EPS and XPS waste necessitates a multifaceted approach that encompasses both on-site and off-site strategies, innovative material choices, and efficient waste stream management. The work explores various technologies and processes, each tailored to address specific challenges in the waste management workflow.

Mobile crushing and compacting units emerge as successful tools for on-site processing, enabling the reduction of waste volume and size directly at construction sites [69], [70]. This not only minimizes transportation costs and environmental impact but also streamlines logistics and enhances the efficiency of subsequent recycling processes [71]. However, the financial investment required for such specialized machinery and the need for trained personnel pose challenges, particularly if smaller amounts of materials are handled. The logistical coordination of on-site processing with ongoing construction activities and the subsequent transportation of processed waste to recycling facilities further add to the complexity.

The work underscores the importance of material separation and sorting in the recycling process. On-site segregation of different waste streams, such as separating fresh EPS and XPS from contaminated materials, is essential for maximizing recycling efficiency. While labor-intensive, this practice ensures that uncontaminated materials such as off cuts can be directly reintroduced into the production cycle, bypassing the need for complex separation processes. Participating in initiatives like EPSolutely, which facilitates the recycling and reintegration of EPS off cuts, can be beneficial. However, challenges arise when construction companies handle off cuts independently. Identifying suppliers who accept returned materials can be tedious and educating construction workers on proper segregation practices requires effort and resources. Furthermore, the collection and return of materials to suppliers adds another logistical step to the construction process.

Off-site processing, involving the transportation of waste to specialized recycling facilities like PS Loop in the Netherlands, is important for handling HBCD-contaminated EPS [56]. The CreaSolv® process employed at PS Loop effectively addresses the challenge of recycling materials containing hazardous flame retardants [23]. However, the transportation of contaminated materials across borders presents logistical and regulatory hurdles. The limited availability of such specialized facilities and the associated costs can also hinder the widespread adoption of this approach. Furthermore, doubts have been raised by the construction and waste management industries regarding the scalability and applicability of this recycling plant, as it is currently in its early stages and not operating at full capacity. PS Loop representatives have also expressed financial concerns, as the costs of incineration have not increased significantly, making material recovery less economically attractive. While substantial investments have

been made in upscaling the recycling plant, operational difficulties persist, raising questions about the long-term viability and effectiveness of this approach. These challenges underscore the need for continued research and development of alternative recycling technologies and the exploration of more economically viable solutions for managing HBCD-contaminated EPS waste.
Mechanical recycling, involving shredding, washing, and pelletizing, is identified as a cost-effective and environmentally friendly option for uncontaminated EPS and XPS waste. However, its applicability is limited to materials free from hazardous contaminants like HBCD, which require specialized solvent-based recycling. The development and implementation of efficient identification via EPD is therefore important for expanding the scope of mechanical recycling and promoting a circular economy for EPS and XPS [72]. The limited access to mechanical recycling plants, due to their rare distribution, further complicates the logistics and economic feasibility of this approach.
The potential of innovative material choices that simplify the recycling process should be incentivized more for construction companies and also advised from consultancies and architects. By using materials that are easier to separate during demolition, such as those with mechanical fixings instead of adhesives, the contamination of EPS and XPS can be minimized, facilitating recycling. However, the higher initial costs of such materials compared to traditional options may hinder their widespread adoption.

These varied technical and logistical considerations, while essential, must be evaluated within the broader context of environmental and economic sustainability. To this end, a comprehensive Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA) were conducted, providing valuable insights into the overall impact of different EPS and XPS waste management strategies.

Costs and Incentives Vary

The comprehensive Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA) conducted providing important insights into the environmental and economic impacts of different EPS and XPS waste management strategies. The LCA, using the ReCiPe 2016 v1.1 Midpoint (H) methodology, reveals that mechanical recycling emerges as the most environmentally sustainable option across various impact categories, including climate change, resource depletion, and human toxicity. This is primarily due to its lower energy consumption and minimal reliance on new resources compared to solvent-based recycling and incineration.
However, the current landscape of EPS and XPS waste management presents a nuanced situation. While mechanical recycling is environmentally preferable, it is not suitable for HBCD-contaminated EPS, which requires specialized solvent-based recycling . This necessitates a two-sided approach, where mechanical recycling is prioritized for HBCD-free materials, and solvent-based recycling is employed for contaminated waste. The solvent-based recycling process, while effective in removing HBCD, presents its own environmental challenges due to the use of solvents and energy-intensive processes. The choice of solvent and the efficiency of solvent recovery significantly influence the overall environmental performance of this method. Therefore, ongoing research and development are necessary to explore alternative, less harmful solvents and optimize energy efficiency in solvent-based recycling [23].
Incineration, despite its potential for energy recovery, consistently ranks as the least environmentally friendly option for EPS and XPS waste management. The combustion process releases a substantial amount of greenhouse gases, contributing significantly to climate change. Moreover, the potential release of toxic substances, including heavy metals, poses risks to human health and the environment [56]. While advancements in energy recovery and pollution control technologies may offer marginal improvements, the inherent nature of incineration as a linear process, where materials are ultimately destroyed, contradicts the principles of a circular economy. Furthermore, incineration does not allow for resource recovery, as valuable materials like polystyrene are lost in the process. This not only wastes resources but also increases the demand for virgin polystyrene production, further increasing the environmental burden associated with the extraction and processing of raw materials. The European Union has set ambitious sustainability goals, including transitioning to a circular economy and reducing greenhouse gas emissions. Relying on incineration as a primary waste management strategy for EPS and XPS hinders progress towards these goals. By prioritizing recycling and reuse, the construction industry can contribute to resource conservation, reduce pollution, and align with the broader sustainability agenda.

The economic analysis further supports the viability of mechanical recycling, as it is the most cost-effective. When comparing the processes to incineration it reveals that incineration is economically attractive as it is the same price or even cheaper then it's compared recycling option. The high costs associated with solvent production, handling, and recovery make solvent-based recycling less economically attractive, especially when considering the relatively low market value of recycled EPS. Incineration, with its potentially offset by energy recovery, remains an attractive option due to infrastructure and low operational expenses.

The economic feasibility of different waste management strategies is not uniform but rather influenced by regional factors. For instance, in regions like Austria and Germany, where incineration costs are high, recycling, even with its associated transportation and processing costs, becomes a financially interesting decision. Conversely, in regions like Belgium, where incineration costs are considerably lower, the economic incentive to recycle diminishes, potentially leading to a preference for incineration despite its environmental drawbacks. This can also be seen when looking at the material processed from the recycling plants. At the solvent-based recycling plant in the Netherlands more Austrian and German material is processed compared to material form the Netherlands or Belgium.

Furthermore, the proximity to recycling facilities plays an important role in determining the economic viability of different recycling methods. Regions with closely accessible recycling plants may favor this method due to reduced transportation costs and logistical complexities. On the other hand, regions further away from such facilities might not consider recycling, despite their higher incineration costs, as more economically viable option due to the transportation burden associated with EPS and XPS waste.

The LCCA underscores the importance of considering these regional variations in waste management decision-making. A one-size-fits-all approach may not be optimal, as the economic feasibility of each strategy depends local factors such as incineration costs, transportation distances, and the availability of recycling infrastructure. By tailoring waste management strategies to the specific economic and logistical context of each region, the construction industry can optimize both environmental and economic outcomes.

The Role of Policy and Regulations

While technological innovation and mindful material selection are pivotal, the regulatory landscape surrounding EPS and XPS waste management plays an important role in determining the feasibility and effectiveness of recycling efforts. Existing regulations, both at the national and European Union levels, aim to promote sustainable practices and reduce the environmental impact of construction waste. However, the effectiveness of these regulations and their impact on different stakeholders remain critical areas of inquiry.

The legal requirement to incinerate or solvent-recycle HBCD-containing EPS and XPS [21], coupled with the prohibition on processing XPS without proof of composition, can deter construction companies from pursuing recycling options. These regulations, while well-intentioned, may inadvertently incentivize less sustainable practices due to the associated costs and complexities. A potential solution could involve revising these regulations to allow for the recycling of HBCD-containing materials under controlled conditions, similar to the approach taken by PS Loop in the Netherlands.

The European Union's ambitious sustainability goals, including transitioning to a circular economy and reducing greenhouse gas emissions, provide a broader context for EPS and XPS waste management. However, the specific regulations targeting these materials and their implementation across member states require further examination. A comparative analysis of national regulations and their effectiveness in promoting EPS and XPS recycling could reveal best practices and areas for improvement. Harmonizing regulations across the EU could also create equal opportunities for recycling companies and incentivize cross-border collaboration in waste management.

To foster a more circular economy for EPS and XPS, a shift in mindset is necessary. This involves moving away from a linear "take-make-dispose" model towards a more integrated approach that considers the entire lifecycle of these materials. Policymakers, industry leaders, and researchers need to collaborate to develop a comprehensive regulatory framework that incentivizes sustainable practices, supports technological innovation, and addresses the economic and logistical barriers to recycling. By aligning regulations with the principles of a circular economy, the construction industry can transform EPS and XPS waste from an environmental burden into a valuable resource.

8
Conclusion

This work investigated the potential of innovative approaches to recycling and reusing EPS and XPS waste in the construction industry. It displays a gap between theoretical solutions and practical implementation due to economic, logistical, and material-specific challenges. The construction industry's commitment to sustainability demands new approaches to managing waste, especially materials like EPS and XPS. While various methods exist for recycling these materials, challenges related to their inherent properties, such as low density and varying contamination levels, often hinder their effective recycling and reuse. To advance the industry towards a more circular economy, it is imperative to thoroughly understand the characteristics of EPS and XPS waste, identify the most promising repurposing strategies, and evaluate existing recycling practices to pinpoint areas for improvement. This work looks into these critical areas, exploring the technical, logistical, and environmental aspects of EPS and XPS recycling and reuse within the construction sector.

Material Properties

EPS and XPS waste present unique recycling challenges due to their inherent material characteristics. EPS's low density and air content make it bulky and costly to transport and process. Furthermore, the composition of EPS can vary, with different additives and fire retardants complicating separation processes. XPS, with its higher density and rigid structure, requires more intensive recycling techniques. Varying levels of contamination, such as glue and mortar, and bitumen, further complicate recycling, requiring separation before processing. Understanding the unique characteristics of EPS and XPS waste is crucial for tailoring effective recycling strategies and identifying appropriate applications for the recycled materials.

Repurposing EPS and XPS

Repurposing EPS and XPS waste into viable construction materials holds significant potential, though challenges remain. For instance, EPS can be incorporated into lightweight concrete, offering benefits such as reduced weight and improved thermal insulation. However, EPS concrete has a lower structural strength than traditional concrete, limiting its applicability in load-bearing structures. While recycled XPS can be used for insulation, achieving a high-quality, reusable material requires overcoming the challenge of removing contaminants. Although repurposed EPS can contribute to reducing material use and building weight, its non-biodegradable nature and the difficulty in separating it for further recycling raise concerns about its long-term environmental impact. In contrast, when recycled correctly, both EPS and XPS can offer excellent thermal insulation properties.

Evaluating Current Recycling and Reuse Practices

A significant disconnect exists between theoretical recycling solutions and their practical implementation in the construction industry. While technologies like solvent-based recycling (CreaSolv®) and mechanical recycling exist, their adoption is limited due to accessibility, cost, logistics, and lack of awareness. This work identified potential improvements, such as on-site sorting and processing, to enhance recycling practices within the industry. To effectively address the challenges posed by waste contamination, collaboration between construction companies and waste management companies is important. Such partnerships can enable construction companies to benefit from larger projects, reduce waste generation, and lower overall costs. Construction companies should explore partnerships with waste management companies to establish on-site sorting and processing facilities, enabling more efficient and cost-effective recycling.

Waste Stream Characteristics and Management Strategies

This research identified three main waste streams generated at construction sites: offcut material, glue and mortar contaminated material, and bitumen contaminated material. These streams exhibit unique characteristics and recycling challenges. Offcuts, being fresh and uncontaminated, are the easiest to recycle. Contaminated materials, however, require more complex separation and processing techniques. To optimize recycling rates and resource recovery, separate collection systems for each waste stream at construction sites are recommended, along with specific processing methods for each type of contamination.

Technical and Logistical Aspects

Effective on-site processing of EPS and XPS requires specific technologies and processes. Mobile crushing and compacting units, which can be transported to different sites, offer significant benefits in reducing transportation costs and improving logistical efficiency. However, transporting contaminated materials over long distances presents challenges, highlighting the need for specialized recycling facilities like solvent-based recycling in the Netherlands. Understanding the technical and logistical aspects of EPS and XPS waste management is crucial for implementing more efficient and sustainable on-site waste management solutions.

Environmental Impacts and Life Cycle Analysis

The comprehensive Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA) revealed that mechanical recycling is the most environmentally sustainable and economically viable option for EPS and XPS waste management. While solvent-based recycling offers resource recovery potential, its environmental performance depends on solvent choice and energy source. Incineration, despite energy recovery, remains the least desirable option due to its high environmental burden. The economic analysis highlighted the cost-effectiveness of mechanical recycling compared to solvent-based recycling and incineration.

By investing in the right technology, and promoting a circular economy, the construction industry can reduce environmental impact and costs by making recycling more efficient. The industry should consider investing in the following:

- On-site sorting and processing using machinery for crushing and separation. This is a cost-effective way to reduce contamination and improve recycling efficiency.
- Specialized recycling facilities like PS Loop, which can handle HBCD-contaminated waste, can be made more accessible by streamlining transportation and permitting processes.
- Incentives for recycling such as grants and special taxes, to make recycling more economically attractive for construction companies.

By implementing these solutions, the construction industry can move toward a more circular economy, significantly reducing its environmental footprint and achieving greater cost-effectiveness.
These are examples of the innovative approaches that can be taken to make the construction industry more sustainable. The key is to focus on collaboration and shared responsibility between stakeholders. The industry should also invest in development of tayloring technologies to their need to improve the efficiency and effectiveness of recycling.

9

Recommendations and Limitations

Recommendations

To address the pressing issue of waste within the construction industry, a fundamental shift from our current linear economy to a circular one is required. Resource recovery is important in this transition. To foster a more sustainable and economically viable construction industry, it is essential to improve the management of EPS and XPS waste. These recommendations are based on an analysis of the current challenges and opportunities in EPS and XPS recycling, as detailed in this work. By addressing the economic, logistical, and technical barriers to recycling, the construction industry can minimize waste, conserve resources, and reduce the environmental impact of these materials.

- Considering On-Site Waste Management: Construction company could determine the most cost effective and efficient methods for on-site management with a focus on sorting and separating EPS and XPS waste directly at construction sites. Investing in mobile crushing equipment can streamline this process and reduce transportation and waste management costs. This will help to minimize contamination and maximize recycling efficiency.
- Foster Collaboration and Knowledge Exchange: Construction companies, waste management entities, and policymakers should actively collaborate and share knowledge to develop and implement effective recycling strategies. This includes raising awareness about recycling options, providing training on proper waste management, and establishing clear guidelines and incentives for recycling.
- Exploration of Innovative Recycling Technologies: Solvent-based recycling of contaminated EPS and XPS offers potential for significant waste reduction but remains largely unproven at an industrial scale. Further research is crucial to determine its economic feasibility and environmental impact compared to existing methods. Furthermore, the development of new recycling technologies presents a significant opportunity for EPS and XPS consumers. Companies should actively monitor and evaluate these emerging strategies to identify those that offer the greatest potential for economic and environmental benefit.
- Advocate for Supportive Policies and Regulations: Governments and regulatory bodies should execute policies and regulations that incentivize sustainable construction practices, including recycling. This could involve financial incentives, stricter waste disposal regulations, and the development of standardized recycling practices.
- Design for Recyclability: Architects, engineers, and construction companies should consider the end-of-life of EPS and XPS during the design phase of construction projects. This includes choosing materials that are easier to separate and recycle, such as those with mechanical fixings instead of adhesives, and prioritizing the use of recycled materials whenever possible.

By adopting these recommendations, the construction industry can move towards a more circular economy for EPS and XPS, where waste is minimized, resources are reused, and the environmental impact of these materials is significantly reduced. This shift towards sustainability is not only an environmental imperative but also an economic opportunity, as it can lead to cost savings, resource efficiency, and a more resilient construction sector.

Limitations

A notable limitation of this work is the reliance on industry data. The primary data sources, such as interviews and site visits, while valuable for real-world insights, introduces potential biases and limitations in data collection. The willingness of companies to disclose information, particularly regarding costs and specific processes, can vary, leading to potential gaps or inconsistencies in the data. Additionally, the evolving nature of recycling technologies and regulations necessitates continuous updates and revisions to ensure the accuracy and relevance of the findings. The limited operational history of innovative recycling facilities like PS Loop, which is still in its early stages of industrial-scale trials, poses challenges in obtaining reliable long-term performance data. The scalability and economic viability of such technologies require further validation through extended operational periods and comprehensive data collection. The reliance on assumptions and estimations in the LCA and LCCA, due to the lack of readily available data for certain processes, introduces a degree of uncertainty in the results. While efforts were made to ensure the accuracy and representativeness of the data, the inherent limitations of modeling and assumptions should be acknowledged when interpreting the findings.

A persistent challenge of recycling EPS and XPS waste is posed by material contaminated with bitumen. The inherent difficulty in separating these materials, due to their adhesive properties and complex composition, highlights a significant gap in current recycling technologies. Existing processes are not equipped to effectively handle such complex waste streams, leading to the disposal of valuable materials through incineration or landfilling. This limitation underscores the need for continued research and development of innovative separation techniques that can address the specific challenges posed by bitumen-contaminated EPS and XPS waste.

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A

LCA results

Solvent based recycling									
Category - ReCiPe 2016 v1.1 midpoint (H)	Total	Methanol	Cyclohexane	Ethanol	EU-28: Waste	EU-28: Diesel	EU-28: water	GLO: Truck	NL: Electricity
Climate change, default, excl biogenic carbon [kg CO2 eq.]	415	34,6	84,9	30,8	106	19,4	0,00878	115	23,5
Climate change, incl biogenic carbon [kg CO2 eq.]	446	35,2	85,9	31,2	125	20,3	0,01	121	26,6
Fine particulate matter formation [kg PM2.5 eq.]	0,233	0,00804	0,02	0,00739	0,00603	0,0168	4,03E-06	0,169	0,00498
Freshwater consumption [m3]	-56,2	-8,05	-13,3	-4,64	-2,44	-5,38	-0,00985		-22,4
Freshwater ecotoxicity [kg 1,4 DB eq.]	0,0623	0,00401	0,0255	0,00639	0,00117	0,0244	1,96E-05	2,21E-08	0,000911
Freshwater Eutrophication [kg P eq.]	0,00237	3,20E-05	5,85E-05	4,52E-05	0,00176	0,000413	1,15E-06		4,94E-05
Human toxicity, cancer [kg 1,4-DB eq.]	0,113	0,00927	0,0429	0,0145	0,00248	0,0352	9,58E-05	0,000547	0,00758
Human toxicity, non-cancer [kg 1,4-DB eq.]	26,5	1,22	9,69	2,35	0,249	12,7	0,00462	0,000464	0,319
Ionizing radiation [kBq Co-60 eq. to air]	0,451	0,0488	0,0704	0,0299	0,0206	0,0496	8,52E-05		0,231
Marine ecotoxicity [kg 1,4-DB eq.]	0,182	0,0108	0,0726	0,0184	0,0028	0,0739	2,80E-05	1,48E-06	0,00324
Marine eutrophication [kg N eq.]	0,00837	0,000138	0,000445	0,000221	0,00501	0,00208	2,24E-06		0,000434
Photochemical ozone formation, ecosystems [kg NOx eq.]	1,6	0,036	0,0761	0,0305	0,0268	0,0421	1,17E-05	1,37	0,0195
Photochemical ozone formation, human health [kg NOx eq.]	1,59	0,0353	0,0719	0,0292	0,0264	0,0397	1,16E-05	1,36	0,0194
Stratospheric ozone depletion [kg CFC-11 eq.]	6,09E-05	5,77E-06	1,01E-05	6,88E-06	2,88E-06	1,94E-05	6,43E-09	1,07E-05	5,22E-06
Terrestrial acidification [kg SO2 eq.]	0,696	0,0242	0,0644	0,0237	0,0176	0,0604	1,03E-05	0,491	0,015
Terrestrial ecotoxicity [kg 1,4-DB eq.]	46,1	4,73	17,2	4,84	3,67	11,4	0,00232	5,49E-05	4,14

Figure A.1: LCA results solvent based recycling

Mechanical recycling						
Category - ReCiPe 2016 v1.1 midpoint (H)	Total	DK: Electricity	EU-28: Diesel	EU-28: waste on landfill	GLO: Truck, 12 - 14t	GLO: Truck, 12 - 14t
Climate change, default, excl biogenic carbon [kg CO2 eq.]	214	51,4	23,3	1,36	125	12,5
Climate change, incl biogenic carbon [kg CO2 eq.]	239	68,4	24,4	1,43	132	13,2
Fine particulate matter formation [kg PM2.5 eq.]	0,244	0,0184	0,0202	0,00215	0,185	0,0185
Freshwater consumption [m3]	-2,30E+03	-2,30E+03	-6,45E+00	-8,30E-01		
Freshwater ecotoxicity [kg 1,4 DB eq.]	0,033	0,00357	0,0292	0,000184	2,42E-08	2,42E-09
Freshwater Eutrophication [kg P eq.]	0,000743	0,000245	0,000496	2,34E-06		
Human toxicity, cancer [kg 1,4-DB eq.]	0,0862	0,0429	0,0422	4,48E-04	0,000597	5,97E-05
Human toxicity, non-cancer [kg 1,4-DB eq.]	16,6	1,27	15,2	0,116	0,000506	5,06E-05
Ionizing radiation [kBq Co-60 eq. to air]	0,688	0,625	5,96E-02	3,49E-03		
Marine ecotoxicity [kg 1,4-DB eq.]	0,101	0,0111	0,0887	0,000901	1,62E-06	1,62E-07
Marine eutrophication [kg N eq.]	0,00442	0,00191	0,00249	1,33E-05		
Photochemical ozone formation, ecosystems [kg NOx eq.]	1,75	0,0564	0,0505	0,00663	1,49	0,149
Photochemical ozone formation, human health [kg NOx eq.]	1,75	0,0561	4,76E-02	6,56E-03	1,49	0,149
Stratospheric ozone depletion [kg CFC-11 eq.]	5,63E-05	1,99E-05	2,33E-05	2,67E-07	1,17E-05	1,17E-06
Terrestrial acidification [kg SO2 eq.]	0,727	0,0594	7,25E-02	6,15E-03	0,535	0,0535
Terrestrial ecotoxicity [kg 1,4-DB eq.]	32	16,1	13,7	2,2	5,99E-05	5,99E-06

Figure A.2: LCA results mechanical recycling

Incineration				
Category - ReCiPe 2016 v1.1 midpoint (H)	Total	EU-28: Diesel	EU-28: Polystyrene in waste incineration	GLO: Truck
Climate change, default, excl biogenic carbon [kg CO2 eq.]	3,43E+03	8,82	3,37E+03	52,3
Climate change, incl biogenic carbon [kg CO2 eq.]	3,44E+03	9,24	3,37E+03	55
Fine particulate matter formation [kg PM2.5 eq.]	0,12	0,00765	0,0353	0,0769
Freshwater consumption [m3]	-42,2	-2,44	-39,8	
Freshwater ecotoxicity [kg 1,4 DB eq.]	0,0132	0,0111	0,00216	1,01E-08
Freshwater Eutrophication [kg P eq.]	0,000219	0,000188	3,16E-05	
Human toxicity, cancer [kg 1,4-DB eq.]	0,024	0,016	0,00774	0,000249
Human toxicity, non-cancer [kg 1,4-DB eq.]	6,55	5,75	0,795	0,000211
Ionizing radiation [kBq Co-60 eq. to air]	0,545	0,0226	0,523	
Marine ecotoxicity [kg 1,4-DB eq.]	0,0406	0,0336	0,00704	6,74E-07
Marine eutrophication [kg N eq.]	0,00138	0,000944	0,00044	
Photochemical ozone formation, ecosystems [kg NOx eq.]	0,799	0,0191	0,158	0,622
Photochemical ozone formation, human health [kg NOx eq.]	0,794	0,018	0,156	0,62
Stratospheric ozone depletion [kg CFC-11 eq.]	2,14E-05	8,82E-06	7,71E-06	4,86E-06
Terrestrial acidification [kg SO2 eq.]	0,429	0,0275	0,178	0,223
Terrestrial ecotoxicity [kg 1,4-DB eq.]	9,91	5,2	4,71	2,49E-05

Figure A.3: LCA results incineration

B

Detailed Sample Preparation and Analytical Procedures for FTIR and DSC

This appendix provides a detailed explaination of the sample preparation methodologies and analytical procedures for the Fourier Transform Infrared Spectroscopy (FTIR) and Differential Scanning Calorimetry (DSC) analyses conducted on EPS samples recovered from bitumen-contaminated construction waste.

B.1. Sample Origin and Challenges in Separation

The EPS samples analyzed originated from the bituminous roofing system of a building demolished in Austria, constructed around 1970. This building lacked detailed material documentation, necessitating thorough analysis to determine the composition of the insulation material and its potential for recycling. The primary challenge encountered was the strong adhesion of the bituminous membrane to the EPS insulation, making their separation difficult. This adhesion is due to the inherent properties of bitumen, a highly viscous viscoelastic material that softens upon heating and adheres strongly to various surfaces.

B.2. Sample Preparation and Analysis: FTIR Spectroscopy

B.2.1. FTIR Analysis Procedure and Principles

FTIR spectroscopy relies on the principle that different chemical bonds absorb infrared light at specific frequencies. When infrared light passes through a sample, the molecules absorb radiation at frequencies corresponding to their vibrational modes. By analyzing the pattern of absorption and transmission, a unique ”fingerprint” spectrum is generated, which can be used to identify the functional groups and chemical constituents present in the sample.

In this study, a Thermo Fisher Scientific spectrophotometer was employed for FTIR analysis. The EPS sample was placed directly onto the instrument's attenuated total reflectance (ATR) crystal, a component designed for analyzing solid and liquid samples directly without requiring further sample preparation. The instrument emitted infrared light through the sample, and the ATR crystal measured the light that passed through it. The absorbance at different wavenumbers was recorded, generating a spectrum representing the unique chemical fingerprint of the sample.

The acquired spectra were then compared to a reference polystyrene spectrum to assess the purity of the recovered EPS. The degree of overlap between the sample spectrum and the reference spectrum provided a measure of the similarity in chemical composition. Any significant deviations or additional peaks in the sample spectrum indicated the presence of other substances, such as additives, contaminants, or degradation products.

B.2.2. Sample Preparation for FTIR

- Manual Separation: The initial step involved manually separating the EPS insulation from the bituminous membrane using a knife. While seemingly straightforward, this step proved labor-intensive and yielded imperfect separation due to the nature of the bitumen. As highlighted before, achieving complete separation of EPS from complex matrices, such as those found in environmental samples, is challenging and often requires a combination of techniques.
- Size Reduction: The partially cleaned EPS fragments were subjected to size reduction. Separating the contaminated EPS beads from the uncontaminated EPS beads to a particle sizes around 10 mm to 15 mm. These were then used as the FTIR samples.

B.3. Sample Preparation and Analysis: Differential Scanning Calorimetry

B.3.1. DSC Analysis Procedure and Principles

DSC is a thermal analysis technique that measures the difference in heat flow between a sample and a reference material as a function of temperature or time while subjected to a controlled temperature program. It provides information about the thermal transitions of a material, such as its melting point, glass transition temperature, crystallization temperature , and specific heat capacity. These transitions manifest as peaks or shifts in the DSC curve, which plots heat flow versus temperature.

In this study, a PekinElmer DSC 6000 instrument was used for analysis. The sealed aluminum crucible containing the EPS sample was placed in the DSC cell alongside an empty reference crucible. Both crucibles were then subjected to a controlled temperature program, typically involving heating and cooling cycles at a constant rate (e.g., 10°C/min) under a controlled atmosphere (nitrogen in this case). The DSC instrument constantly measured the temperature difference between the sample and reference crucibles. Any thermal event in the sample, such as melting, crystallization, or a glass transition, resulted in a change in heat flow to maintain the same temperature as the reference. The DSC software recorded these changes in heat flow as a function of temperature, generating a DSC curve.

Analysis of the DSC curve allowed for the identification of specific thermal events and their corresponding temperatures. By comparing the observed transitions with known values for EPS, the material's thermal behavior was characterized, and the presence of any impurities or additives could be inferred.

B.3.2. DSC Sample Preparation

The initial steps for DSC sample preparation were identical to those of FTIR and involved manual separation of EPS from the bituminous matrix.

- Weighing and Encapsulation: Approximately 10 mg (0.01 g) of the EPS beads was carefully weighed using a microbalance and transferred into aluminum crucibles (40 µL). Aluminum is a suitable material for DSC crucibles due to its high thermal conductivity, ensuring uniform heat distribution to the sample. The crucibles were hermetically sealed to prevent sample loss or contamination during analysis. The small size and the low density of the EPS powder presented challenges during encapsulation, requiring careful handling to ensure proper sealing and avoid air gaps that could affect heat flow measurements.
- Importance of Sample Mass: The small sample mass is critical in DSC to ensure uniform heating and cooling rates throughout the sample. Larger samples can lead to thermal gradients, resulting in inaccurate measurements of transition temperatures.