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Case study on insulation

An example of chemical considerations for sustainable plastics design

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An example of chemical considerations for sustainable plastics design

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Foreword

This case study was developed to provide input to and inform the development of guidance on General Considerations for Design of Sustainable Plastics from a Chemical Perspective. Four case studies were developed as concrete examples to inform these considerations. Two in the plastic packaging sector: biscuit wrapping and detergent bottles; two in the construction sector: flooring and insulation. For this purpose, the case studies start from the premise that plastic material will be used and therefore alternative material selection is not considered. They focus on environmental sustainability aspects related to chemical selection, taking into account health protection across the product life cycle. They do not address cost, performance, and chemical/material availability information, which would need to be considered in an application scenario. They also do not consider a discussion of social and environmental justice impacts.

The examples of material selection within the case studies are developed in the context of the information gathered for the case studies to exemplify the sustainable design process and to highlight key considerations. To make actual decisions about material selection other factors would also need to be considered (as outlined above) and the analysis could be further informed by elements such as life cycle assessment comparing alternatives and a full review of regulatory restrictions.

This document is based on a draft report developed by the Healthy Building Network for the project and was reviewed by an OECD expert group supporting this project, which also provided a number of inputs. It was further reviewed by the OECD Working Parties on Risk Management and on Resource Productivity and Waste. Additionally the report was discussed at an OECD workshop on developing the general considerations for design of sustainable plastics from a chemical perspective held in March 2021.

This report is published under the responsibility of the OECD Chemicals and Biotechnology Committee in collaboration with the OECD Environmental Policy Committee.

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Executive Summary

The OECD is conducting a project on design of sustainable plastics from a chemical perspective which aims to identify the key considerations regarding environmental/health sustainability that should be examined along the product life cycle when chemicals are selected at the design stage, as well as the potential trade-offs between these considerations. Case studies on particular sector/product combinations have been elaborated to inform the development of the general considerations. This case study aims to increase the awareness of environmental and health impacts and potential policy interventions to lead to sustainable plastic products from a chemicals perspective using insulation as an example.

Building on the findings from the recent OECD report “Considerations and Criteria for Sustainable Plastics from a Chemical Perspective” this case study lays out actionable Sustainable Plastic Goals that could be applied across the product life cycle to help develop sustainable durable plastic products.

Behind packaging, the building and construction industry is the second largest consumer of plastics, comprising 16% of global plastic production. For this reason building products – in particular insulation products – are used as example durable plastic products for this case study. The four product types included are:

- Expanded polystyrene (EPS),
- Extruded polystyrene (XPS),
- Polyisocyanurate (polyiso), and
- Spray polyurethane foam (SPF).

An analysis of the chemicals used in the manufacturing of the base polymers, the manufacturing of the products themselves, the installation materials, and recycled content highlighted many opportunities for mitigation of impacts from the use of hazardous substances. These opportunities include consideration of different designs, different materials, different manufacturing processes and various policy instruments that could reduce the impacts of the product throughout the life cycle.

This analysis also revealed trade-offs that exist between different material choices. For example, an insulation product that is designed to chemically react at the build site as applied can allow the insulation to form to the surroundings in which it is installed, and can provide air sealing as well as insulative properties. However, when that product includes hazardous substances, this means that hazardous substance exposures are possible during more life cycle stages than if the product completed reacting in the manufacturing stage. Adherence of the insulation to surrounding materials may also make the insulation and those other materials more difficult to reclaim or recycle.

This analysis highlighted data gaps that exist both in chemicals used and released at various life cycle stages and in the amount of hazard data available on those chemicals.

Through this analysis a set of criteria was generated to benchmark and compare material alternatives across life cycle stages. Example criteria include:

- The base polymer chosen uses the least hazardous chemicals in the manufacturing and produces the least hazardous production emissions.
- Additives are fully assessed for hazards and are the least hazardous available.
- The product can be reclaimed and reused.
- The material is recyclable at the end of life into products with equal or greater value.

These considerations can be used by design teams, procurement professionals, or regulators to benchmark current practices, make material selections, and measure progress towards the aspirational sustainable plastic goals. While the considerations were developed with plastic insulation in mind, they are relevant for any durable plastic product.

The insulation product analysis and the sustainable plastic goals are also used to define and align policy instruments that can encourage and reward work towards sustainability outcomes. For example, policies restricting the use of hazardous substances coupled with extended producer responsibility programs can facilitate circular product design.

The sustainable plastic goals outlined in this case study are ambitious. Current products are unlikely to meet all of the criteria. While they may not be immediately achievable, the considerations provide a pathway toward truly sustainable plastic products. This paper focuses on comparing plastic insulation products; however, additional insulation materials such as fiberglass, mineral wool, cork, cellulose, etc. should be considered and compared from a sustainability perspective in actual product design situations. In product design, innovation may require the consideration of vastly different materials versus making incremental improvements in chemistry for a particular type of product.

Project teams need to prioritise which sustainability elements are most important and relevant for their applications and how to deal with gaps in understanding. This report includes examples of how to use the considerations to compare different product types.

1. Introduction

1.1. Purpose of case study

This case study aims to increase the awareness of environmental and health impacts and potential policy interventions to lead to sustainable plastic products from a chemicals perspective using insulation as an example.

Building on the findings from the recent OECD report "Considerations and Criteria for Sustainable Plastics from a Chemical Perspective" (OECD, 2018a), this case study lays out actionable goals that could be applied across the product life cycle to help develop sustainable durable plastic products. These goals are used throughout the rest of the case study to:

- Consider key potential environmental and health impacts at each life cycle stage (source materials, product manufacture, use phase, end of life), focusing on chemical selection using four representative plastic insulation product types as examples.
- Compare results and discuss trade-offs between sustainable plastic goals.
- Generate common criteria for durable plastic product design.
- Identify policy instruments to facilitate progress towards sustainable plastic goals consistent with the OECD Policy Principles for Sustainable Materials Management (Box 1.1).

These criteria can be used by design teams to benchmark current practices, make material selections, and measure progress towards the aspirational sustainable plastic goals.

Box 1.1. OECD Policy Principles for Sustainable Materials Management (OECD, 2010)

1. Preserve natural capital
2. Design and manage materials, products, and processes for safety and sustainability from a life cycle perspective
3. Use the full diversity of policy instruments to stimulate and reinforce sustainable economic, environmental, and social outcomes
4. Engage all parts of society to take active, ethically-based responsibility for achieving sustainable outcomes

This case study will not address all elements critical to sustainable products and processes. It is mainly focused on environmental sustainability aspects related to chemical selection, taking into account health protection across the product life cycle. It does not address, but should be considered in context with, information on cost, performance, and availability. It also does not include consideration of non-plastic alternatives or discussion of social and environmental justice impacts. It should also be informed by life cycle assessment (LCA) and a full review of regulatory requirements. Cleaning and other maintenance practices used over the product life cycle could also have chemical impacts for different product types, but they are beyond the scope of this case study. In addition, it is acknowledged that there are data gaps in this analysis. Data gaps are likely to exist in the application of this framework to other material comparisons.

The Key Concepts and Definitions section includes definitions of key terms such as “hazardous substances” or “extended producer responsibility” and key concepts such as “life-cycle thinking” or “class-based approach” used throughout this case study.

Box 1.2. Key Concepts and Definitions Used in this Case Study:

Alternatives assessment. Alternatives assessment is a decision framework used to compare and select alternative chemicals, materials, products, or processes. The objective of an alternatives assessment according to the Interstate Chemicals Clearinghouse Alternatives Assessment Guide "is to replace chemicals of concern in products or processes with inherently safer alternatives, thereby protecting and enhancing human health and the environment." Alternatives may be chemicals, materials, or disruptive product designs. Several frameworks exist that help users consider hazards, life cycle impacts, trade-offs, and uncertainties when comparing alternatives (OECD, no date a). Resources such as the OECD Substitution Toolbox can be used to identify tools for substitution and alternatives assessment.

Circular economy. Per the Ellen MacArthur Foundation, "A circular economy seeks to rebuild capital, whether this is financial, manufactured, human, social, or natural. This ensures enhanced flows of goods and services." A circular economy designs out waste and pollution, keeps products and materials in use, and regenerates natural systems (MacArthur, n.d.).

Class-based approach (Blum Arlene et al., 2015; Gore et al., 2015). Often, chemicals with similar chemical structures have similar functionality and similar inherent hazards. The class-based approach refers to the concept of moving away from regulating one problematic chemical at a time and toward reducing the use of entire classes of chemicals of concern. Regulating one chemical at a time is impractical and can foster regrettable substitutions. Examples of chemical classes might include molecules that share a common toxic element, such as lead compounds; halogenated organic compounds, such as brominated organic flame retardants; or chemicals that share a common function, such as antimicrobials (GSPI, 2013). Examples of such approaches implemented by policy makers include the U.S. Environmental Protection Agency's (EPA) cumulative assessment of risk from pesticides and the European Union directive limiting total perfluoroalkyl substances (PFAS) in drinking water (O. US EPA, 2015; Directive (EU) 2020/2184, 2020).

For some chemicals in this case study, a class-based approach was used to highlight groups of chemicals identified by the scientific community as having structural or functional similarities that may contribute to negative human health and environmental impacts (DiGangi et al., 2010; Blum Arlene et al., 2015; Gore et al., 2015; Medicine et al., 2019; Kwiatkowski et al., 2020; Engel et al., 2021). Not all chemicals in a class are necessarily problematic. A comprehensive hazard assessment can be used to identify when specific chemicals may have different hazards than those associated with the class overall.

Common Product Profile. A Common Product profile is a list of substances that are most commonly present in a product type as delivered to building sites in North America. The profiles are not specific to any manufacturer. Common Products are organised by chemical function. The profiles provide the most common substance identified among the products surveyed serving each function in a given product type, a hazard screening for each substance, and a general description of the product type. Common Products are based upon a wide range of publicly available information, including product declarations, patents, and chemical suppliers' brochures that detail the functional uses of various additives. For a more detailed description of the research methodology see https://pharosproject.net/common-products/methodology.

Extended Producer Responsibility. Extended Producer Responsibility (EPR) refers to a policy instrument where producers must take financial and/or physical responsibility for the treatment or disposal of post-consumer products. The theory behind EPR is to incentivise product design for the environment, public recycling, and sustainable materials management (OECD, no date b).

Hazard assessment. Very few of the tens of thousands of chemicals in use today have been fully assessed for health hazards. To enable informed decision making, the expansion of publicly available chemical hazard assessments (CHA) is critical. A full hazard assessment method uses authoritative and screening hazard lists, results from regulatory tests, information from the toxicological literature, and data from new approach methods (NAMs) such as those from analogous chemicals and modelled data where needed to characterise or estimate the hazards associated with a particular chemical. Hazards include human health hazards such as carcinogenicity, endocrine disruption, acute toxicity, and irritation; environmental hazards such as aquatic toxicity, bioaccumulation, and persistence; and physical hazards such as flammability and reactivity. Several methodologies exist, all of which are based at least in part on the Globally Harmonised System for Classification and Labelling (GHS) (UNECE, no date). Methods include the Cradle to Cradle Material Health Methodology (Cradle to Cradle Products Innovation Institute, no date), the GreenScreen for Safer Chemicals (Clean Production Action, no date) and the U.S. EPA's Design for the Environment Program Alternatives Assessment Criteria for Hazard Evaluation (O. US EPA, 2014). Most CHA methods also identify where data gaps exist for particular hazard endpoints.

Hazardous substances. For the purpose of this case study "hazardous substances" are defined as Substances of Very High Concern for REACH (SVHC), those on the ChemSec Substitute it Now List (SIN), Persistent Organic Pollutants identified by the Stockholm Convention (POP), ozone-depleting substances (ODS), and hydrofluorocarbons (HFCs) or other substances with high global warming potential (GWP) identified by the Montreal Protocol unless otherwise noted (UNEP, 1987; Regulation (EC) No 1907/2006, 2006; United Nations, 2016; UNEP, 2018b; ChemSec, no date b, no date c). For the purposes of this study chemicals are defined as having high global warming potential if they appear in Annex F of the Montreal Protocol, or are defined as an ODS elsewhere in the Montreal Protocol and have a 100-year global warming potential on par with the substances listed in Annex F. These lists were chosen due to their international applicability and should be considered as a simple proxy for hazardous substances identification. There are many other hazards that could be relevant to specific product use and exposure scenarios. For example, chemicals that are respiratory irritants or sensitisers may not be on the hazardous substance lists cited above. But they may still be substances of concern to those who manufacture or use plastic products. To view additional hazard lists identified by OECD that may be used to screen out problematic chemicals and alternatives see Exhibit 5 from OECD's Guidance on Key Considerations for the Identification and Selection of Safer Chemical Alternatives (OECD, 2021). The long-term goal should be to have chemical hazard assessments for all chemicals in the product life cycle and to use that information to eliminate the use of hazardous substances, especially those chemicals likely to result in exposure to humans or the environment. Full CHAs are preferred to list-based hazard identification. In the absence of full CHAs for all chemicals identified in this case study, and in an effort to identify those chemicals of highest concern, the five lists above were chosen for this case study.

Hierarchy of controls (NIOSH, 2015). The Hierarchy of Controls ranks the most effective ways to protect workers by controlling exposures. Elimination, or physically removing the hazard, is the most effective way of controlling exposure. Use of personal protective equipment is the least effective method of controlling exposure and should be only used when more effective controls are not feasible.

Figure 1.1. The National Institute for Occupational Safety and Health (NIOSH) Hierarchy of Controls

Source: NIOSH, 2015. Figure © by NIOSH and available from https://www.cdc.gov/niosh/topics/hierarchy/default.html

Life cycle assessment. The International Standards Organisation (ISO) has defined LCA as: "A technique for assessing the environmental aspects and potential impacts associated with a product by:

- Compiling an inventory of relevant inputs and outputs of a product system,
- Evaluating the potential environmental impacts associated with those inputs and outputs, and
- Interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study" (ISO, no date).

LCA technique examines impacts at each life cycle stage, typically including end of life. Standards such as ISO 14040 define the principles on how to conduct and report LCA studies (ISO, no date).

Life-cycle thinking. Life-cycle thinking considers potential impacts of a product or process at all stages of the product’s life cycle. This approach helps identify key life cycle stages where impacts occur and avoids shifting impact burdens from one stage to another, from one country to another, from one impact category to another, or from one generation to another (Galatola, no date). Life-cycle thinking can be applied to considerations not typically included in life cycle assessment tools, such as exposure to toxic substances by humans or other receptors.

OECD Policy Principles for Sustainable Materials Management. Principles developed by the OECD as guidance for specific governmental policies to shift behaviour of government, businesses, organisations, and people towards meeting the needs of the society in a sustainable way. These principles include: 1) Preserve natural capital; 2) Design and manage materials, products, and processes for safety and sustainability from a life-cycle perspective; 3) Use the full diversity of policy instruments to stimulate and reinforce sustainable economic, environmental, and social outcomes; and 4) Engage all parts of society to take active, ethically-based responsibility for achieving sustainable outcomes (OECD, 2010).

Persistent Organic Pollutant (POP). Persistent Organic Pollutants (POPs) are defined by the Stockholm Convention as organic chemical substances that remain intact for many years and become widely distributed throughout the environment as a result of natural processes involving soil, water, and air. They accumulate in the fatty tissue of living organisms, concentrating as they move up the food chain, and are toxic to both humans and wildlife (UNEP, 2018b, no date c).

Post-consumer material. U.S. Green Building Council defines post-consumer material as “waste material generated by households or by commercial, industrial and institutional facilities in their role as end-users of the product, which can no longer be used for its intended purpose” (U.S. Green Building Council, 2009).

Pre-consumer material. U.S. Green Building Council defines pre-consumer material as “material diverted from the waste stream during the manufacturing process. Reutilisation of materials (i.e., rework, regrind or scrap generated in a process and capable of being reclaimed within the same process that generated it) is excluded” (U.S. Green Building Council, 2009).

Product content disclosure. Full disclosure of product contents, also known as product transparency, allows for more informed choices and helps prevent regrettable substitutions. Public disclosures of building products are available on the Health Product Declaration (HPD) Public Repository (HPDC, no date) or the International Living Future Institute’s Declare database (ILFI, no date). Products with full materials disclosure move beyond those that disclose the minimum needed to produce a compliant safety data sheet, make claims the products are “free of” specific chemicals or materials, or “compliant with” certification standards or green building credits, toward the disclosure of all the substances that are in the product. HPD is the building industry’s collaborative, user-designed open standard for disclosure of product contents and associated health hazards. Products with public HPDs that have all contents characterised, screened, and identified to 100 ppm can be considered “fully disclosed.” Further, product content disclosures that have been third-party verified are typically of higher quality and are more complete than those that have not been verified.

Qualitative exposure assessment. A quantitative exposure assessment measures exposure to humans (via dermal, oral, or inhalation routes) or exposure to the environment (water, air, or soil). In contrast, a qualitative exposure assessment screens chemicals for their potential for exposure based on, but not limited to, physical chemical properties of the chemical, how that chemical is used in a product, and how that product is used. Chemical release reporting can also be used as a proxy for volume. For the purposes of this case study, a simple example screening method was used to determine if release of the chemical could be considered negligible. This method was adapted from ECHA’s recent publication “Describing uses of additives in plastic material for articles and estimating related exposure. Practical guide for industry” (ECHA, 2020). During product use, exposure to additives could be considered negligible if:

- Percentage in the product is below some threshold, i.e. <0.1%
- Substance has very high molecular weight, very low solubility in water, high octanol water partition coefficient, low vapour pressure, and no reaction generating smaller molecules.

- Substance is reacted into a polymer chain and is known not to degrade into toxic environmental transformation products.
- Substances may not be considered to be of negligible exposure per criteria above if they are:
    - additives meant to move to the surface or to work as plasticisers.
    - additives in products that are subject to leaching promotion, abrasion, or volatilisation due to use at high temperatures.

Note: Qualitative exposure assessments can be sufficient to discriminate between alternatives and to minimise risk to human health and the environment. But when more information is needed, a quantitative exposure assessment on a specific insulation product is recommended.

Regrettable substitution. When a single chemical is phased out due to known hazards, the replacement may be a chemical with similar or different and potentially worse hazards. For example, as Bisphenol A (BPA) was phased out of bottles, cans, and receipts due to endocrine disrupting concerns, it was replaced by Bisphenol S (BPS) and Bisphenol F (BPF). Unfortunately, BPS and BPF are closely related structurally to BPA and have similar endocrine disruption concerns (Tragger, 2019). Another example of a regrettable substitution is the substitution of toxic chlorinated solvents in brake cleaners with n-hexane, a neurotoxicant.

Substances of Very High Concern (SVHC). SVHCs are defined in Article 57 of Regulation (EC) No 1907/2006. These include substances that are 1) carcinogenic, mutagenic, or toxic to reproduction (CMR) in category 1A or 1B in accordance with section 3.6 of Annex I to Regulation (EC) No 1272/20082, 2) substances that are persistent, bioaccumulative, and toxic (PBT) or very persistent and very bioaccumulative (vPvB) according to the criteria in REACH Annex XIII and/or 3) substances that are identified, on a case-by-case basis, that cause an equivalent level of concern as CMR or PBT/vPvB substances (Regulation (EC) No 1907/2006, 2006).

Substitute it Now List (SIN List). The SIN List identifies hazardous chemicals used in a range of products and processes around the world. It is developed by the non-profit organisation ChemSec in collaboration with scientists and technical experts, as well as environmental, health, and consumer organisations, and, according to ChemSec, represents a “preview” of chemicals that may be designated as Substances of Very High Concern, based on the REACH criteria (ChemSec, no date b).

Sustainable Materials Management. The OECD defines Sustainable Materials Management as “an approach to promote sustainable materials use, integrating actions targeted at reducing negative environmental impacts and preserving natural capital throughout the life cycle of materials, taking into account economic efficiency and social equity” (OECD, 2010). Sustainable materials management grew out of OECD work on waste management. It takes a holistic approach that is intended to align and integrate policies that reduce negative impacts from chemicals and materials in environmental, industrial, and societal systems.

1.2. Insulation Landscape

Plastic production has increased exponentially over the last 70 years, reaching 430 million tons in 2019 (OECD Plastics Outlook database). Behind packaging, the construction industry is the second largest user of plastics, comprising 17% of global plastic production (OECD Plastics Outlook database).

Thermal insulation comes in various forms, including batts or blankets, rigid boards, loose fill, and spray foam insulation. It is made from a variety of materials including glass fibre, mineral wool, cork, cellulose, foamed plastic and wood fibres. These materials offer a wide range of thermal conductivities for any given thickness. In the US, plastic foam insulation accounts for nearly half of the insulation sold (Energy Efficiency for All, 2019). In the EU, plastic foam insulation is around 42% of the thermal insulation market (Pavel and Blagoeva, 2018).

The global insulation market is growing and is predicted to reach $80 billion USD (about 68 billion euros) by 2026 (Global Market Insights, Inc, 2019). Increased use of insulation has been driven by increased demands for residential and commercial construction, as well as increased energy costs and regulations related to energy conservation (ReportLinker, 2016; Global Market Insights, Inc, 2019). Plastic foam insulation is projected to grow the most rapidly due to its low thermal conductivity (high R-value per inch) (ReportLinker, 2016).[1] Energy-efficiency retrofits are also introducing new insulation materials into existing buildings.

In general, insulation is designed to last the lifetime of a building. Plastic foam insulation is typically designed to last around 60-75 years. (EPS Industry Alliance, 2017; SPFA, 2018; Owens Corning, 2019; PIMA, 2020).

1.2.1. Product Types Selected for Case Study

This case study considers four types of plastic insulation:

1. Expanded polystyrene (EPS),
2. Extruded polystyrene (XPS),
3. Polyisocyanurate (polyiso), and
4. Spray polyurethane foam (SPF).2

These insulation materials are commonly used and represent different polymer chemistries, different additive concerns and a range of exposure considerations at different stages of the product life cycle. While there may be other types of plastic insulation, these four types cover the majority of the plastic insulation market (Pavel and Blagoeva, 2018; Grand View Research, 2019).

The polymer itself accounts for about 75-95% of the total weight of a plastic insulation product. Common additives include blowing agents to create the foam structure and influence insulative properties, and flame retardants to meet flammability standards. Blowing agents off-gas to different degrees during manufacturing, but make up about 2-9% of the product by weight as delivered to the job site. Flame retardants typically make up about 1-6% of the weight of the product, but may account for up to 20% in open cell spray foam insulation (Icynene, 2017, 2019). Other additives that are used in some of the product types include process aids, stabilisers, and facing materials. Some foam insulation also contains recycled content.

Product content and process chemistry information provided throughout this case study is based on Common Product research unless otherwise noted. See the key concepts section for a definition of Common Products and a description of the research process. Details on the typical chemical content, the functional roles of that content, and percentage in the product is provided in Annex A for each insulation type.

Notes

[1] Low thermal conductivity or high R-value mean higher insulative performance.

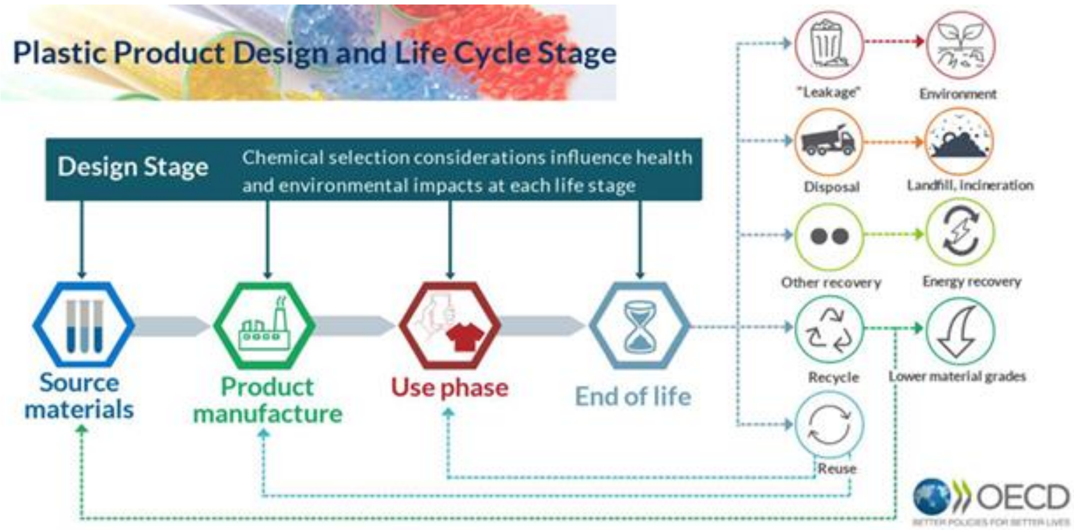
[2] SPF can be either open cell or closed cell. Open cell and closed cell SPF are similar in composition, but use different blowing agents and have different finished product characteristics.

2. Chemical considerations throughout the life cycle

Building products of any type have potential human health and environmental impacts from chemical exposure at every stage of the product life cycle, including production, installation, use, and disposal or recycling. Life-cycle thinking, defined in the key concepts section above, considers potential impacts of a product or process at all stages of the product's life cycle. This approach helps identify key life cycle stages where impacts occur and avoids shifting impact burdens, for example, from exposure to users during product use to exposure to workers during manufacture. The different feedstocks, monomers, catalysts, and functional additives used in different plastic products may result in exposures to a variety of substances. The type of polymer and additives also impacts the recyclability of insulation materials and associated chemical releases at end of life. Figure 2.1 illustrates how life-cycle thinking is used to consider impacts from a chemical perspective throughout the stages of a plastic product life cycle and how design choices can change these impacts.

The goal of life cycle thinking is to reduce impacts across the full life cycle and to advance sustainable materials management. One can intervene at any point in the life cycle. Sustainable materials management is inherently circular. For simplicity, the considerations in this case study are presented starting with the design stage because that is where the full system is likely to be considered. Interventions at any life cycle stage may result in changes in impacts at other life cycle stages. While this is inherently circular, it is difficult to communicate if not laid out step by step in a linear fashion.

Figure 2.1. Plastic Product Design and Life Cycle Stage



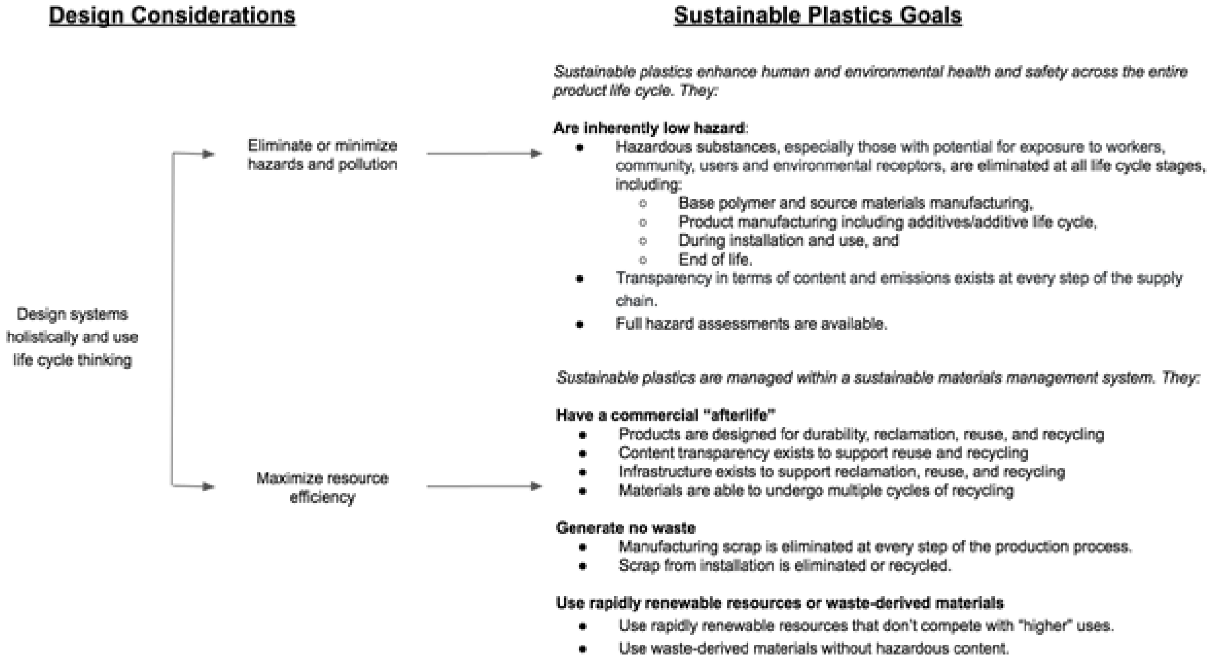
Risk is a function of both hazard and exposure. Exposures to chemicals can occur at any of the life cycle stages. Exposure assessments may be quantitative or qualitative. Exposure is dependent on many factors including, for example, the physical chemical properties of the chemical of interest, its volume of use, the product properties, manufacturing conditions, use of personal protective equipment, how and where the product is installed and used, and how the product is managed at the end of its useful life. For the purposes of this case study a simple qualitative exposure screening approach is applied based on inherent chemical properties and product design. See Key Concepts and Definitions for a definition of a qualitative exposure assessment and a description of the screening process. In addition, occupational exposure to chemicals used to make the base polymers and products is assumed.

In cases where qualitative exposure assessment does not help discriminate between materials, a quantitative exposure assessment can be performed. However, these assessments can be costly and highly context-specific. Qualitative exposure assessment can provide strong indicators of a chemical's exposure potential and help identify opportunities for mitigation of risk from exposure to hazardous substances. The Hierarchy of Controls (see definition in Key Concepts and Definitions section) presents a spectrum of options to reduce primarily worker exposure to chemicals of concern. Based on the Hierarchy of Controls, it is more effective to eliminate chemicals of concern or substitute them with safer alternatives than it is to reduce exposure by using process controls or personal protective equipment. Understanding the inherent exposure and hazard potentials of chemicals in products can help project teams prioritise reducing the use of the most hazardous substances and the use of hazardous substances with highest potentials for exposure.

In the OECD report "Considerations and Criteria for Sustainable Plastics from a Chemical Perspective," sustainable plastics are defined as "...plastic materials used in products that provide societal benefits while enhancing human and environmental health and safety across the entire product life cycle. To be considered sustainable, plastics must be managed within a sustainable materials management system (a circular economy) (MacArthur, n.d.) to avoid the creation of waste, toxics and pollution." (OECD, 2018a) OECD defines sustainable materials management as "An approach to promote sustainable materials use, integrating actions targeted at reducing negative environmental impacts and preserving natural capital throughout the life cycle of materials, taking into account economic efficiency and social equity."

In Figure 2.2 below, the OECD definition of sustainable plastics and sustainable materials management are combined with the American Chemical Society Green Chemistry Institute's Design Principles for Sustainable and Green Chemistry and Engineering to generate a set of actionable Sustainable Plastics Goals. The goals are further broken into measurable subgoals that can be used to work toward sustainable plastic products (American Chemical Society (ACS) Green Chemistry Institute (GCI), 2015).

Figure 2.2. Design considerations used to work towards sustainable plastics goals



Sustainable plastics enhance human and environmental health and safety across the entire product life cycle. They:

Are inherently low hazard:

- Hazardous substances, especially those with potential for exposure to workers, community, users and environmental receptors, are eliminated at all life cycle stages, including:
    - Base polymer and source materials manufacturing,
    - Product manufacturing including additives/additive life cycle,
    - During installation and use, and
    - End of life.
- Transparency in terms of content and emissions exists at every step of the supply chain.
- Full hazard assessments are available.

Sustainable plastics are managed within a sustainable materials management system. They:

Have a commercial "afterlife"

- Products are designed for durability, reclamation, reuse, and recycling
- Content transparency exists to support reuse and recycling
- Infrastructure exists to support reclamation, reuse, and recycling
- Materials are able to undergo multiple cycles of recycling

Generate no waste

- Manufacturing scrap is eliminated at every step of the production process.
- Scrap from installation is eliminated or recycled.

Use rapidly renewable resources or waste-derived materials

- Use rapidly renewable resources that don't compete with "higher" uses.
- Use waste-derived materials without hazardous content.

The sustainable plastics goals cited above are lofty, however, having these goals in mind allows scientists, product design teams, and policy makers to ask questions that will help to create both supply and demand for more sustainable plastics. These goals serve as the framework for analysis for comparing the four plastic insulation products in this case study. The sections below present key considerations for sustainable plastic insulation products from a chemicals perspective at different life cycle stages following the sustainable plastics goals. On the path toward sustainable plastic products, this is an approach that can be applied to identify trade-offs and data gaps and to measure progress in any plastic building product.

2.1. Design

The primary job of insulation materials is to reduce the transfer of heat from inside a building to outside, and vice versa. Insulation materials provide benefits by making buildings more comfortable and reducing energy usage. The insulative properties, conveyed as R-values or thermal conductivity, are paramount. In some cases, such as retrofit applications, there may be limitations to the thickness of material that can be used, so the insulative performance per inch of material can also be important. Insulation may be required to meet certain flammability requirements, and it may be desirable for the insulation to have certain compressive strength, vapour permeability, or air barrier properties for particular applications. Designers can also consider sustainability goals, for example, to eliminate or minimise the use or generation of hazardous substances and pollution throughout the product's life, incorporate recycled content, and design for reuse and recyclability. It is these latter design features that will be explored in this case study.

2.1.1. Key Considerations - Design

In general, products are designed to meet product use requirements, minimum performance standards, and scenarios (insulative performance; conditioned or unconditioned space;

attic, wall, below slab, etc.). Design considerations may include: What conditions will it need to withstand (exposure to moisture, compression, etc.)? How long is the product intended to last? What is the intended end of life plan, and what are the available options for value recovery? Below are key considerations related to this initial design phase based on the three high level considerations for sustainable plastic products.

- Design systems holistically and use life cycle-thinking
    - Were project team members trained on safe and circular design principles and life-cycle thinking?
    - Is there a process in place to consider, test, develop, and encourage innovative designs to achieve sustainability goals?
    - Is the product designed for a commercial afterlife?
    - Is the designed end of life reasonable given the available regional infrastructure for recycling, material take back programs, etc.?
    - Can the product undergo multiple cycles of recycling, and is the recyclate a viable alternative to virgin materials?
    - Does the product design minimise material diversity/complexity (heterogeneous vs homogeneous)?
- Maximise resource efficiency
    - Were alternative product designs compared based on resource use? For example, designs that minimise energy consumption, material use, and waste production?
    - Are measures in place to track energy consumption, material use, and waste production throughout the supply chain? Are there goals to reduce energy consumption, material use and waste production?
- Eliminate and minimise hazards and pollution
    - Were different designs considered and compared based on ability to minimise the use or generation of hazardous substances at each life cycle stage? See each life cycle stage section for more details.

2.1.2. Example Trade-offs - Design

It may not be possible to meet all sustainability criteria simultaneously, and trade-offs may be necessary. The physical form of the insulation product may impact the possible chemistries and the life cycle stages at which there may be exposure. For example, a product that is designed to be spray-applied at the job site may limit the base polymer options that can be used and may also lead to the presence of unreacted chemicals during both manufacturing and installation phases. During the design stage, manufacturers can prioritise impacts and trade-offs early in product development. Teams can prioritise which sustainability elements are most important to incorporate into their design and how to deal with gaps in understanding. These sustainability elements may be tied to specific brands and corporate sustainability policies.

2.2. Production of the Base Polymer

2.2.1. Base Polymer Source Materials

The inputs used in the production of a base polymer for plastic insulation include the monomer(s), catalysts, and initiators. This case study also considers the primary chemicals, often derived from petroleum or natural gas, and intermediates used to produce the monomer. Impacts from a chemicals perspective include consideration of the hazards of these inputs as well as releases of hazardous substances from the manufacturing facilities. Two primary polymer chemistries are used in plastic foam insulation: polystyrene, used in EPS and XPS insulation, and polyurethane/polyisocyanurate, used to make SPF and polyiso. Both polyurethane and polyisocyanurate are based on a reaction of isocyanates and polyols and use similar process chemistry, therefore they are combined in this section for simplicity. Table 2.1. and 2.2. summarise the chemical inputs and possible exposure scenarios for the base polymer materials. Whether comparing products for exposures to hazardous chemicals using life-cycle thinking or using full life cycle assessment, it is essential to draw clear system boundaries to allow for consistent and equivalent comparisons.

Table 2.1. Chemicals that may be used in production of polystyrene base polymer source materials

	Chemical Name	SVHC‡	SIN List	POP	ODS	High GWP
Primary Chemicals	Ethylene					
	Benzene		●			
Intermediates	Ethylbenzene					
Monomers	Styrene		●			
Catalysts/ Process Chemicals for Different Stages	Zeolites (catalyst for ethylbenzene production)					
	Aluminium chloride (catalyst for ethylbenzene production)					
	Benzoyl peroxide (polymerisation initiator)					
	Azobisisobutyronitrile (polymerisation initiator)		○			
	P-benzoquinone (polymerisation inhibitor)					
Recycled Polymer Input	EPS/XPS containing HBCD	○	○	○		
Hazardous Substance Outputs/Emission	Data Gap					
Exposure Scenarios to Consider	• Occupational exposure. During the manufacturing stage occupational exposure potential is assumed for all primary chemicals, intermediates, monomers, and process chemicals. • Human and environment via environmental releases during manufacture					

Note:

● The chemical is identified on the hazard list indicated. No alternatives were identified for this chemical function.

○ The chemical is identified on the hazard list indicated. The chemical is not used in all regions, being phased-out, and/or alternative chemicals are available for this process.

‡ The chemicals flagged in this column are identified as Substances of Very High Concern (SVHC) for REACH, either banned unless authorised, candidate list, or prioritised for listing.

Source: Sources for Tables 2.1. and 2.2. (Franklin Associates, 2011a, 2011b; Lithner, 2011; Rossi and Blake, 2014; Healthy Building Network, no date c; National Center for Biotechnology Information, no date)

Table 2.2. Chemicals that may be used in production of Polyurethane and Polyisocyanurate base polymer source materials

	Chemical Name	SVHC‡	SIN List	POP	ODS	High GWP
Primary Chemicals	Benzene		●			
	Ammonia					
	Hydrogen					
	Methanol					
	Carbon Monoxide					
	Sodium Hydroxide					
	Chlorine					
	Propylene					
	Ethylbenzene					
	Isobutene					
	MTBE					
	Sucrose					
Intermediates (pMDI)	Nitric Acid					
	Nitrobenzene	●	●			
	Aniline		●			
	Formaldehyde		●			
	Phosgene					
	4,4'-Methylenedianiline (MDA)	●	●			
Intermediates (Polyol)	1,2-Propylene Oxide	○	○			
	Propylene Chlorohydrin					
	Ethylene Oxide		○			
Monomers (pMDI)	MDI					
Monomers (Polyol)[a]	Ethylene Oxide		○			
	Formaldehyde		○			
	Dimethyl Terephthalate					
	Ethylene Glycol					
	2,5-Diaminotoluene					
	Phenol					
	Potassium hydroxide	●	●			
	Mercury[b]		○			

	Asbestos[b]		○			
	PFAS diaphragm or Membrane[b]	○ *	○ *	○ *		
	N/A					
	Data Gap					
	• Occupational exposure. During the manufacturing stage occupational exposure potential is assumed for all primary chemicals, intermediates, monomers, and process chemicals. • Human and environment via environmental releases during manufacture					

Note:
● The chemical is identified on the hazard list indicated. No alternatives were identified for this chemical function.
○ The chemical is identified on the hazard list indicated. The chemical is not used in all regions, being phased-out, and/or alternative chemicals are available for this process.
‡ The chemicals flagged in this column are identified as Substances of Very High Concern (SVHC) for REACH, either banned unless authorised, candidate list, or prioritised for listing.
* This SVHC, SIN List, or POP association is identified based on a chemical class-based approach. Not every chemical in these groups will appear on the indicated hazard list, but the list does contain multiple CASRNs within the chemical class.
a A wide range of chemicals can be used to produce polyols. Because of the wide range of possibilities, this table highlights the three SVHC or SIN list chemicals associated with the polyols that were identified in HBN's Common Product Research as example process chemicals, as well as several additional chemical inputs that may be used.
b These technologies are alternatives to each other, but no alternatives to these technologies were identified.
Source: Sources for Tables 2.1. and 2.2. (Franklin Associates, 2011a, 2011b; Lithner, 2011; Rossi and Blake, 2014; Healthy Building Network, no date c; National Center for Biotechnology Information, no date)

Polystyrene Production - Reagents and Process Chemicals

The production of polystyrene is based on a standard chemistry with minimal opportunities to substitute or vary the materials used. Benzene, a primary chemical input, is on the SIN List. Azobisisobutyronitrile, an initiator that may be used in polymerisation, is also on the SIN List. Alternative initiators that are not SVHC, SIN List, or POPs lists are available.

Polystyrene Production - Monomer

Polystyrene is manufactured using the monomer styrene, which is on the SIN List. The production of the polymer takes place separately from the manufacturing of the insulation product.

Polystyrene Production - Emissions

Emissions throughout the supply chain of polystyrene are a data gap in this analysis. Some styrene and ethylbenzene emissions are expected for polystyrene manufacture, with variations in levels of emissions between plants (US EPA, 1991). Because communities adjacent to manufacturing or disposal facilities – often called fenceline communities – can be adversely impacted by release of hazardous substances, this is an important data gap to fill. When hazardous substances are not entirely avoidable within base polymer production, an understanding of the different processes and different emission controls utilised throughout the supply chain can help a product manufacturer choose a base polymer or supplier to minimise hazardous substance use and/or emissions.

Polyurethane/Polyisocyanurate - Reagents and Process Chemicals

Polyurethane/polyisocyanurate chemistry has many steps involving many chemicals and some opportunities to make different chemical choices. The primary chemicals that react to make the polyurethane polymer are a pre-polymer material called a polyol and an isocyanate or polyisocyanate.

Isocyanate manufacturing involves chlorine which is needed to synthesise the intermediate phosgene. Production of chlorine gas relies on one of four different technologies. Older technologies utilise mercury cells and asbestos diaphragms. Newer technologies either use per- and polyfluoroalkyl substance (PFAS) diaphragms or PFAS-coated membranes. While most chlorine production utilises the latter two technologies, all four methods of production are still used (Vallette, 2018, 2019; U.S. Geological Survey, 2020).[1] Each production technology has trade-offs from a chemical hazard perspective. Mercury and asbestos are on the SIN list, and some of the chemicals in the PFAS class are identified as SVHCs, with many more PFAS chemicals unstudied for health impacts. Intermediates in isocyanate manufacture include SVHCs nitrobenzene and 4,4'-methylenedianiline (MDA) as well as SIN List chemicals formaldehyde and aniline.

The polyol monomers can have various inputs, some of which may be hazardous, such as 1,2-propylene oxide, an SVHC, or ethylene oxide, a SIN List chemical.

Polyurethane/Polyisocyanurate Production - Monomers

The commonly used isocyanate monomer in the SPF and polyiso supply chain is diphenylmethane diisocyanate (MDI). This may be reacted to generate polymeric MDI (pMDI) prior to insulation manufacture. Isocyanates, including MDI, are not SVHCs, SIN List, or POP chemicals, but are globally recognised as respiratory sensitisers (ECHA, no date a; Korean National Institute of Environmental Research, no date; New Zealand EPA, no date; NITE-CHIRP, no date; Safe Work Australia, no date). Isocyanates have been a leading cause of work-related asthma in industrialised countries, though the reported incidence has declined in recent years (Rüegger et al., 2014; US Occupational Safety and Health Administration, 2014; Lefkowitz et al., 2015; Rosenman, Reilly and Pickelman, 2020; The National Institute for Occupational Safety and Health (NIOSH), 2020).

Some manufacturers have worked on alternative, isocyanate-free technologies for spray foam insulation (Olang, 2013; SprayFoam.com, 2017). It is unclear whether any are currently available commercially, but this could potentially avoid the inherent hazards of MDI in manufacturing and installation, if the alternative chemicals are fully assessed to be of low hazard. While personal protective equipment and administrative or engineering controls can be implemented to control exposures, the most effective ways to protect workers are to eliminate the hazard or substitute it with a lower hazard.

Polyisocyanurate is commonly manufactured using MDI or polymeric MDI and a polyester polyol (Dow, 2014; PIMA, 2020). The polyol can have various monomer inputs.

Polyurethanes in spray polyurethane foam insulation are manufactured using MDI and pMDI along with multiple types of polyols that can vary widely in the monomers used to make them. The monomers may include SIN List chemicals such as formaldehyde and ethylene oxide. Polyols may also have some biobased or recycled content (Bioplastics Magazine, 2017; Huntsman Building Solutions, 2021).

Polyurethane/Polyisocyanurate Production – Emissions

Emissions throughout the supply chain of polyurethane/polyisocyanurate precursors are a data gap in this analysis. Some emissions are expected, with variations in levels of emissions between plants and depending on the specific polyols used. Because communities adjacent to manufacturing or disposal facilities can be adversely impacted by release of hazardous substances, this is an important data gap to fill.

Recycled Polymers

Use of recycled polymer feedstocks can eliminate impacts from the production of virgin base polymers. However, with recycled polymers comes the potential for unintentional content in terms of additives from the original product or contaminants introduced during the product's life.

Polystyrene - Unintentional content from recycled feedstocks

EPS insulation appears to typically contain recycled content from its own manufacturing process, in which case it would not introduce any different chemicals to the product (EPS Industry Alliance, 2017). Some EPS products can contain up to 25-35% recycled content, which is primarily pre-consumer (Insulfoam, 2016; EPS Industry Alliance, no date; Insulation Corporation of America, no date). The nature of the recycled content is not disclosed, but given that polystyrene typically makes up more than 95% of the product weight, it is expected that this recycled content is polystyrene and likely EPS scrap from other facilities. Some EPS insulation in Europe may contain up to 10% post-consumer polystyrene recovered from domestic waste sorting systems, including materials such as polystyrene cups and trays (Versalis, no date).

XPS insulation may contain post-consumer recycled content (Kingspan Insulation, 2014; Owens Corning, 2019, 2020). This may be EPS beads or densified EPS foam (Owens Corning, 2019). Less than 5% post-consumer polystyrene is reported in XPS products in Europe (EXIBA, 2019). It is unclear whether the pre-consumer recycled EPS foam or the post-consumer polystyrene used is from packaging, insulation, or another application.. For any post-consumer EPS or XPS insulation recycled back into new insulation, the flame retardant hexabromocyclododecane (HBCD), an SVHC and POP, is a concern and could lead to exposure for recycling workers and dispersion into the broader environment when the material is processed. To address this, closed-loop recycling processes under development in the EU and Canada aim to remove HBCD from EPS, allowing it to be recycled into insulation free of HBCD (PolyStyreneLoop Cooperative, no date; Polystyvert, no date). See the Product Manufacture and End of Life sections for more information on HBCD and the closed-loop recycling process.

Polyurethane/Polyisocyanurate - Unintentional content from recycled feedstocks

Polyiso and SPF insulations do not typically contain recycled content (SPFA, 2018; PIMA, 2020). Since this is a thermoset chemistry, the polymer cannot be mechanically recycled and reformed into new products, except potentially as a filler. Chemical recycling could potentially generate recycled feedstocks for polyiso or SPF, but this does not appear to be currently done. Chemical recycling can require the use of additional hazardous substances and other environmental impacts that would need to be compared to virgin production impacts.

2.2.2. Key Considerations - base polymer source materials

When choosing the base polymer for an insulation product, one should consider how the alternatives compare in terms of volume of hazardous substances used and/or emitted from manufacturing, potential for exposure from manufacturing, the availability of alternative synthesis routes or manufacturing processes that avoid or reduce hazardous substances, and the data gaps that exist. As outlined above, multiple routes of synthesis or chemical inputs exist in particular for polyurethane/polyisocyanurate. Specific supply chains can also influence the impacts of a polymer choice, depending on emissions from specific manufacturing facilities. For these reasons, understanding the impacts of the plastic material used depends on understanding the supply chain and the chemical inputs.

- Design systems holistically and use life-cycle thinking
    - Were project team members trained on alternatives assessments?
    - Is there a process in place to consider, test, develop, and encourage innovative base polymer types?
    - Were alternative base polymers considered and compared using impact assessment tools?
    - Was the chosen base material analysed using impact assessment tools to identify hotspots and find opportunities for improvement?
    - Were different base polymer manufacturing facilities considered and compared by measures implemented to reduce environmental impacts?

- Maximise resource efficiency
    - Were alternative base polymers considered and compared by resource use? For example, are any based on renewable resources or waste-derived materials?
    - Were alternative base polymers considered and compared by ability to be recycled in the region used?
    - For the chosen base polymer, were availability of alternative synthesis routes considered and compared by resource use?
    - For the chosen base polymer, are there procedures in place to track, report, and set goals to reduce resource use?

- Eliminate and minimise hazards and pollution
    - Were alternative base polymers considered and compared by use and release of hazardous substances and resource use?
    - For the chosen base polymer, were availability of alternative synthesis routes considered and compared by use and release of hazardous substances and resource use?
    - Were different base polymer manufacturing facilities considered and compared by measures implemented to measure, disclose, and reduce the use and release of chemicals of concern?
    - If hazardous substances cannot be avoided, are they used in a closed system to reduce or avoid exposures?
    - If recycled content is used as a base polymer source, is the source material known? Has it been tested for legacy hazardous substances? And/or is content transparency documentation available and complete for the material? How much control does the manufacturer have over recycled feedstock? Can they reliably obtain feedstock free of toxic residuals?
    - If no base polymers of inherently low hazard source materials (primary chemicals, intermediates, monomers, and catalysts) were identified, was a desire for green chemistry solutions expressed to the supply chain?

2.2.3. Example Trade-offs - base polymer materials

Neither polystyrene nor polyurethane/polyisocyanurate entirely avoid hazardous substances in the base polymer source materials. The simpler chemistry of polystyrene production means that there are fewer pieces of the supply chain to track and understand, but also fewer options for varying chemical inputs to reduce impacts. Both polymers utilise hazardous chemicals that are key to their chemistry, and both provide some opportunities to choose chemicals for particular functions that are not SVHC, SIN List, or POP chemicals. Overall, polystyrene manufacturing does not use SVHCs or POPs, whereas some SVHCs are common in the supply chain to manufacture polyurethane and polyisocyanurate, in particular, intermediates for MDI. To move further toward inherently low hazard chemicals, a design team can iterate the hazard comparison to consider additional hazards and/or full hazard assessments.

Data gaps can also present a challenge in comparing materials. For example, a significant data gap in this analysis is the lack of emission information throughout the supply chain. Comparable supply chain and chemical emissions data is necessary to make a complete comparison of the two base polymer materials. Manufacturers should not assume there are no sustainability implications when no data is available, but rather should strive to fill data gaps when possible. There can also be significant variation in emissions between manufacturing facilities for the same base polymer material. An understanding of the different processes and different emission controls utilised throughout the supply chain can help a product manufacturer choose, within a given base polymer, which suppliers are minimising the use and release of hazardous substances.

Polyurethane/polyisocyanurate polymers do offer the potential to include biobased content in the polyol portion. If rapidly renewable materials are used that do not compete with “higher” uses, this can help reduce the use of chemicals sourced from fossil fuels. However, the thermoset nature of these materials limits the options for commercial afterlife.

When choosing the base polymer for an insulation product, one should consider how the alternatives compare in terms of volume of hazardous substances, the availability of alternative synthesis routes or manufacturing processes that avoid or reduce hazardous substances and related emissions, and the data gaps that exist, as well as trade-offs with other life cycle stages.

2.3. Product Manufacture

Following the production of the base polymer, these materials are combined with a range of additives to manufacture the insulation itself. Plastic insulation manufacturing processes vary between product types. EPS manufacturers typically receive a pre-made resin consisting of beads of polystyrene and additives, which they then expand and mould into a board (EPS Industry Alliance, 2017). XPS manufacturers receive polystyrene granules and incorporate additives as part of the product manufacturing (Owens Corning, 2019). Polyiso manufacturing involves reacting the raw materials to generate the polymer as part of the product manufacturing (PIMA, 2020). SPF insulation is reacted on site when it is installed in a building, and thus may arguably be considered to be manufactured at that stage. For this analysis, SPF manufacturing will be considered as the actions performed in a factory setting to prepare the two components for sale (SPFA, 2018).[2] The product manufacture stage is also considered to include manufacturing of formulated pellets that are later used for insulation manufacturing, as is the case for EPS. Tables 2.3. to 2.6. summarise some of the primary differences in chemicals used during product manufacturing for the product types being considered.

Table 2.3. Chemicals and materials that may be used during product manufacture of EPS insulation

	Chemical Name	SVHC‡	SIN List	POP	ODS	High GWP
Flame Retardants	Hexabromocyclododecane (HBCD)	○	○	○		
	Butadiene styrene brominated copolymer [CASRN 1195978-93-8]					
Blowing Agent	Pentane					
	Cyclopentane					
	Isopentane					
Catalysts	N/A					
Reactive Monomers	N/A					
Potential Residual Monomer	Styrene		●			
Specialty Additives	Disodium Octaborate Tetrahydrate		○			
Exposure Scenarios to Consider	• Occupational exposure. During the manufacturing stage occupational exposure potential is assumed for all additives, blowing agents, catalysts, and monomers. • Human and environment via environmental releases during manufacture					

Note:

● The chemical is identified on the hazard list indicated. No alternatives were identified for this chemical function.

○ The chemical is identified on the hazard list indicated. The chemical is not used in all regions, being phased-out, and/or alternative chemicals are available for this process.

‡ The chemicals flagged in this column are identified as Substances of Very High Concern (SVHC) for REACH, either banned unless authorised, candidate list, or prioritised for listing.

Source: Sources for Tables 2.3.-2.6. (Icynene, 2016; BASF SE, 2017; NCFI Polyurethanes, 2017; SPFA, 2018; EXIBA, 2019; Henry Company, 2020; Healthy Building Network, no date c)

Table 2.4. Chemicals and materials that may be used during product manufacture of XPS insulation

	Chemical Name	SVHC‡	SIN List	POP	ODS	High GWP
Flame Retardants	Hexabromocyclododecane (HBCD)	○	○	○		
	Butadiene styrene brominated copolymer [CASRN 1195978-93-8]					
Blowing Agent	HFC-134a					○
	HCFC-142b/22 blends[a]				○	○
	HFO-1234ze					
	CO2 and hydrocarbons such as isobutane					

Catalysts	N/A					
Reactive Monomers	N/A					
Potential Residual Monomer	Styrene		●			
Exposure Scenarios to Consider	• Occupational exposure. During the manufacturing stage occupational exposure potential is assumed for all additives, blowing agents, catalysts, and monomers. • Human and environment via environmental releases during manufacture					

Note:

● The chemical is identified on the hazard list indicated. No alternatives were identified for this chemical function.

○ The chemical is identified on the hazard list indicated. The chemical is not used in all regions, being phased-out, and/or alternative chemicals are available for this process.

‡ The chemicals flagged in this column are identified as Substances of Very High Concern (SVHC) for REACH, either banned unless authorised, candidate list, or prioritised for listing.

a As of 2018, China was still reported to be using blends of HCFC-142b/22 (UNEP, 2018a). In 2020, medium and large enterprises in China were reported to be moving towards HFC and CO2-based blowing agents as hydrochlorfluorocarbons (HCFCs) continue to be phased out there (UNEP, 2020c).

Source: Sources for Tables 2.3.-2.6. (Icynene, 2016; BASF SE, 2017; NCFI Polyurethanes, 2017; SPFA, 2018; EXIBA, 2019; Henry Company, 2020; Healthy Building Network, no date c)

Table 2.5. Chemicals and materials that may be used during product manufacture of polyiso insulation

	Chemical Name	SVHC‡	SIN List	POP	ODS	High GWP
Flame Retardants	Tris(2-chloroisopropyl) phosphate (TCPP)		○			
	Reactive non-halogen: Diethyl hydroxymethyl phosphonate					
Blowing Agent	Pentane					
	1-bromopropane		○			
Catalysts	Potassium 2-ethylhexanoate					
	Potassium acetate					
	1,2-Ethanediamine, N1-(2-(dimethylamino)ethyl)-N1,N2,N2-trimethyl-					
Reactive Monomers and Oligomers	Diphenylmethane Diisocyanate (MDI) and/or Polymeric MDI (pMDI)					
	Polyester polyol					
Potential Residual Monomer	N/A					

Exposure Scenarios to Consider	• Occupational exposure. During the manufacturing stage occupational exposure potential is assumed for all additives, blowing agents, catalysts, and monomers. • Human and environment via environmental releases during manufacture

Note:
● The chemical is identified on the hazard list indicated. No alternatives were identified for this chemical function.
○ The chemical is identified on the hazard list indicated. The chemical is not used in all regions, being phased-out, and/or alternative chemicals are available for this process.
‡ The chemicals flagged in this column are identified as Substances of Very High Concern (SVHC) for REACH, either banned unless authorised, candidate list, or prioritised for listing.
Source: Sources for Tables 2.3.-2.6. (Icynene, 2016; BASF SE, 2017; NCFI Polyurethanes, 2017; SPFA, 2018; EXIBA, 2019; Henry Company, 2020; Healthy Building Network, no date c)

Table 2.6. Chemicals and materials used during product manufacture of SPF insulation

	Chemical Name	SVHC‡	SIN List	POP	ODS	High GWP
Flame Retardants	Tris(2-chloroisopropyl) phosphate (TCPP)		●			
Blowing Agent	HFC-245fa (closed-cell SPF)[a]					○
	HCFC-141b (closed-cell SPF)[b]				○	○
	HFO-1233zd (closed-cell SPF)					
	Water (open-cell SPF or closed cell SPF)[c]					
Catalysts	Dibutyltin dilaurate		●			
	Various amine catalysts					
Reactive Monomers and Oligomers	Diphenylmethane Diisocyanate (MDI) and/or Polymeric MDI (pMDI)					
	Polyester polyol					
	Polyether polyol					
	Mannich polyol					
Potential Residual Monomer	Formaldehyde		○			
Exposure Scenarios to Consider	• Occupational exposure. During the manufacturing stage occupational exposure potential is assumed for all additives, blowing agents, catalysts, and monomers. • Human and environment via environmental releases during manufacture					

Note:
● The chemical is identified on the hazard list indicated. No alternatives were identified for this chemical function.
○ The chemical is identified on the hazard list indicated. The chemical is not used in all regions, being phased-out, and/or alternative chemicals are available for this process.

‡ The chemicals flagged in this column are identified as Substances of Very High Concern (SVHC) for REACH, either banned unless authorised, candidate list, or prioritised for listing.

a This is one common HFC that is used in closed-cell SPF insulation. HFC-134a, HFC-227EA, and HFC-365mfc were also identified. All of these blowing agents are listed in Annex F: Controlled Substances under the Montreal Protocol.

b HCFCs continue to be phased out globally but may still be used in spray foam applications in some regions (UNEP, 2020c).

c Water is commonly used as the primary blowing agent in open cell SPF and as a second blowing agent in closed cell SPF. A closed cell SPF product using only water as the blowing agent has been advertised but it is not clear if the product is still available.

Source: Sources for Tables 2.3.-2.6. (Icynene, 2016; BASF SE, 2017; NCFI Polyurethanes, 2017; SPFA, 2018; EXIBA, 2019; Henry Company, 2020; Healthy Building Network, no date c)

2.3.1. Flame retardants

Flame retardants are used in almost all plastic insulation and are commonly halogenated (containing either chlorine or bromine). EPS and XPS manufacturers have historically used the flame retardant hexabromocyclododecane (HBCD), an SVHC due to its persistent, bioaccumulative, and toxic characteristics. HBCD is also a persistent organic pollutant (POP) under the Stockholm Convention. It was added to Annex A in 2013 along with a provision for a time-dependent exemption for HBCD used in EPS and XPS in buildings (UNEP, 2018b). Most of these exemptions have now expired, and China is the only country that still has an active exemption which is due to expire in 2021 (UNEP, no date b). Polyisocyanurate and SPF insulation commonly use the flame retardant tris(2-chloroisopropyl) phosphate (TCPP), which is on the SIN List because it is persistent, mobile, and toxic. Exposures to workers and releases of these flame retardants to the environment are possible in the manufacturing stage. Releases may impact fenceline communities and, given the persistence of flame retardants, the broader environment.

Butadiene styrene brominated copolymer, the polymeric flame retardant now common in EPS and XPS is reported to have the same flame retardant efficiency as HBCD (UNEP, 2012). It has a high molecular weight and low bioavailability and was evaluated to be of low hazard across a suite of GHS endpoints with the exception of medium hazard for eye irritation (US EPA, 2014). The US Environmental Protection Agency (EPA) does note that the butadiene styrene brominated copolymer "is inherently persistent and its long-term behaviour in the environment is not currently known" (US EPA, 2014). Understanding the environmental fate of all polymeric halogenated flame retardants is essential to evaluating them from a sustainable materials management perspective, as brominated and chlorinated flame retardants have long been considered a high priority to avoid by many in the scientific community due to a number of life cycle concerns (DiGangi et al., 2010; Minet et al., 2021).

Halogen-free polyiso products are currently available in some regions (Buhrman, 2017; GAF, 2017). The flame retardant reacts during manufacturing to become part of the polymer. The specific chemical used in products is not publicly disclosed, but patent information suggests it may be diethyl hydroxymethyl phosphonate (Nandi, Wang and Asrar, 2015), which is not an SVHC, SIN List, or POP. See the Use as Installed section below for more details on the flame retardants used in the different product types.

Products without flame retardants are available in certain regions for certain applications where building code allows. California has new legislation allowing polystyrene insulation without flame retardants to be used below grade beneath cement slabs (Melton, 2019; Charbonnet, Weber and Blum, 2020). Products for this application are exempted from meeting the open flame standard that plastic foam insulation must typically meet (Charbonnet, Weber and Blum, 2020). Polystyrene insulation used elsewhere in a building still will require the addition of a flame retardant to meet the open flame testing standard (Charbonnet, Weber and Blum, 2020). Other regions have building codes that consider assembly-level fire performance as opposed to an open flame test of the bare insulation. As a result, for example, flame retardant-free polystyrene boards dominate the market in Scandinavia (Charbonnet, Weber and Blum, 2020) although particular ecolabel programmes, such as Nordic Swan, do have some exemptions for use of butadiene styrene brominated copolymer in EPS and XPS insulation foam in particular scenarios with medium to high risk of fire (Nordic Ecolabelling, 2021).

2.3.2. Blowing agents

Blowing agents are used in all plastic foam insulation, but their specific identities vary between and within product types. EPS and polyiso use pentane blowing agents. One polyiso manufacturer is known to use 1-bromopropane, which is on the SIN List, as a second blowing agent. Open cell SPF uses water as a blowing agent. XPS and closed-cell SPF use halogenated blowing agents such as hydrofluorocarbons (HFCs), hydrofluoroolefins (HFOs) (Healthy Building Network, no date b, no date a, no date d) and carbon dioxide (CO_2). Some regions still use hydrochlorofluorocarbons (HCFCs) (UNEP, 2018a, 2020c). These blowing agents do not have health impact concerns during product manufacturing, but HCFCs are ozone depleters with high global warming potential (GWP), and HFCs also have high global warming potential. HFOs do not themselves have high GWP, but use high GWP and/or ozone depleting substances in the manufacturing process, some of which may also be hazardous, such as carbon tetrachloride, which is on the SIN List (Nair et al., 2013; Liang, Newman and Reimann, 2016; Wang, Tung and Cottrell, 2016). Releases of these and other hazardous substances that may be used in the process are possible. Full consideration of the life cycle chemical and environmental impacts of additive chemicals such as blowing agents is outside the scope of this case study but is an important consideration. This analysis also does not include a full life cycle assessment of overall environmental impacts throughout a product’s life, such as energy savings during use. That information can be used to supplement the chemical hazard analysis.

Non-halogenated blowing agents are commonly used in XPS in Europe (BASF SE, 2017; EXIBA, 2019). These blowing agents do not have high GWP nor does their manufacture require high-GWP chemicals, but these alternatives do lead to a lower insulative performance for the product (JACKON Insulation GmbH, 2015; Energy Efficiency for All, 2018; EXIBA, 2019).

2.3.3. Other additives

Catalysts are required for polymerisation for polyiso and SPF. SPF commonly uses organotin compounds such as dibutyltin dilaurate, which is on the SIN List.

Residual monomers may be present in the already made polymers and polyols. The bigger hazard concern at this stage is potential exposure to reactive monomers. Isocyanates such as MDI are respiratory sensitisers. Manufacturing facilities may be able to use closed systems and ventilation to reduce the potential for exposure (NIOSH, 2014).

Insecticides may be included in some EPS products for specific applications in regions where termite infestation is “very heavy” according to building code. These insecticides can be hazardous. For example, disodium octaborate tetrahydrate, identified in some products, is on the SIN List.

Manufacturing processes influence the need for additional additives. For example, the brominated polymeric flame retardant used in XPS insulation requires stabilisers due to the high processing temperature. Common stabilisers are not SVHCs or on the SIN List.

2.3.4. Key considerations - product manufacture

- Design systems holistically and use life-cycle thinking
    - Were project team members trained on hazard assessments and materials disclosure programs?
    - Is there a process in place to consider, test, develop, and encourage innovative technologies to achieve sustainability?
    - Are measures in place to track and report key sustainability measures?
- Maximise resource efficiency
    - Were different manufacturing processes considered and compared by resource use? For example, were they compared based on ability to minimise energy consumption, material use, and waste production?
    - Are current facilities tracking resource use such as energy, water, and material use? Have they set goals to reduce the use of these resources?
- Eliminate and minimise hazards and pollution
    - Were different manufacturing processes considered and compared based on ability to minimise use and release of hazardous substances and pollution?
    - Are current manufacturing facilities tracking the use and release of hazardous substances and pollution? Are they reporting the results? Have they set goals to reduce the use and release of hazardous substances?
    - Were inherently low hazard additives identified? If no alternatives of inherently low hazard were identified, is the function of that chemical necessary for product performance or can it be removed? If it cannot be removed, was a desire for green chemistry solutions expressed to the supply chain?

2.3.5. Example Trade-offs - product manufacture

Plastic foam insulation materials almost always include blowing agents and flame retardants. As cited above, many of these chemicals are hazardous or they use or generate hazardous substances at other life cycle stages. Additives required for specific functionalities should be selected to minimise hazards throughout the product's life.

Halogenated flame retardants are a concern across plastic foam insulation, but non-halogenated options exist and are in use for some polyiso products. These are expected to be less of a concern, however, public full chemical hazard assessments should be pursued to ensure they are inherently low hazard. Considering performance requirements early in the design process can allow for the selection of a base plastic material for which safer alternative additives, such as a non-halogenated flame retardant, are available. Where building code allows for products that do not contain added flame retardants, they should be avoided altogether.

Halogenated blowing agents have high GWP or use chemicals with high GWP during their manufacture.[3] Non-halogenated alternatives avoid these chemicals, but tend to have lower insulative performance. Innovative product design or additives, or complete reimagining of the materials that make up the product, can be used to maintain or increase performance without adding SVHC, SIN List, or POP chemicals. Increased product complexity or additives included to improve performance must be considered in terms of the potential trade-offs for other life cycle stages. For example, a modified EPS material known as graphite polystyrene (GPS) includes graphite as an additive, which changes the reflection and absorption behaviour to improve insulation performance (Atlas EPS, 2018). This improves thermal resistance by 17-50% over standard EPS for different classifications of EPS while still using a non-halogenated blowing agent (EPS Industry Alliance, 2017; Atlas EPS, 2018). This additional additive may lead to trade-offs at other life cycle stages if there are hazardous substances used to manufacture the additive or if its presence changes how the product can be handled at end of life.

Differences in the type of polymers used can influence options for the insulation manufacturing process and at which stages and how many stages in the life cycle hazardous substances are present. For example, concerns about monomer exposure exist for polyiso manufacturing because the polymer is formed during this stage. Similarly, SPF is still in its unreacted form at the manufacturing stage, and as such, hazardous monomers are a concern. In contrast, polystyrene insulation is manufactured from the polymer. Residual monomers at much lower percentages in the product could be a concern during product manufacturing.

2.4. Use

2.4.1. Installation

EPS, XPS, Polyiso

EPS, XPS, and polyiso insulation have few exposure concerns during installation. Composition is the same during installation as during the product life (see Tables 2.7.-2.9.). For some applications, adhesives may be used that could introduce additional hazardous substances, so mechanical installation is preferred when possible. Adhesives also make reclamation and reuse less plausible at the end of life (EXIBA, 2019). Tape may also be used to seal the seams. Cutting of foam board insulation is usually minimal, but could result in the generation of dust that could expose installers to chemicals of concern or release the chemicals into the environment.

SPF

SPF insulation is delivered to the job site as two separate components and reacts during installation to form a foamed insulation. Composition of the product prior to installation will be the same as identified during the product manufacturing stage (see Table 2.6.). Most SPF insulation must be installed by professional applicators (SPFA, 2018), though some low-pressure systems are available at home improvement retailers and may be purchased by individual consumers (Guo et al., 2017). Hazardous chemicals are given off during the installation process including isocyanates, whose respiratory sensitisation impacts can come both from breathing in vapours and from skin contact with the chemicals (US EPA, 2015; Guo et al., 2017). Spills or leaks and cleaning processes present potential for additional exposure (Guo et al., 2017). A U.S. review of unpublished industrial hygiene studies conducted between 2007 to 2014 indicated that SPF applicators and workers in close proximity to them are potentially exposed to levels of the isocyanate MDI in excess of occupational exposure limits such that personal protective equipment is required (Wood, 2017). Exposure can be mitigated with the use of engineering controls, such as ventilation, and personal protective equipment (PPE). Required PPE for spray foam installation usually includes full body protection in the form of disposable coveralls, chemical-resistant gloves and boots or booties, a hood, and eye and face protection as well as supplied air respirators (Wood, 2017; Sustainable Workplace Alliance, no date; US EPA, no date). Other chemical exposure concerns for installers or those in the area during installation include exposure to TCPP, the common halogenated flame retardant used (Estill et al., 2019).

Building occupants should vacate a building during installation of spray foam insulation and until the foam has finished curing and the building has been ventilated and thoroughly cleaned. The EPA notes that, “It is not clear how much time is needed before it is safe for unprotected workers or building residents to re-enter. Re-entry time is dependent on product formulation and other factors that affect the foam curing rates” (US EPA, no date). ASTM standards provide a method to measure emissions from SPF after installation and a standard is under development to model emissions in a building (ASTM International, 2017, no date). This testing can help inform resident reoccupancy times. Work is ongoing to develop a method to measure emissions during SPF application to help manufacturers determine re-entry times for workers without PPE (American Chemistry Council, 2019; Wieroniey, 2020). Common industry practice is waiting 24 hours after completion of spray foam installation for re-entry (Wood, 2017).

While the industry has taken measures to provide educational materials and many installers likely follow the prescribed guidelines, there are still cases of homeowners or installers who have become ill because of exposure to spray foam (Guo et al., 2017). Problems noted in the last several years by the Occupational Health Clinical Centers in New York include: “possible improper application of the foam; inadequate respiratory protection and ventilation for workers; spray foaming when the building was occupied; re-occupying too soon...; and lack of warning about the health hazards of spray foam insulation for the home owners and workers.” (Lax, Siwinski and Wigmore, 2016; Occupational Health Clinical Centers, 2016)

2.4.2. Use as Installed

Tables 2.7. to 2.10. summarises some of the primary differences between the product types being considered and likely exposure scenarios during product use as installed. This does not include all chemicals that might be present in each product type.

Table 2.7. Chemicals that may be present in EPS insulation during use as installed

	Chemical Name	SVHC‡	SIN List	POP	ODS	High GWP
Flame Retardants	Hexabromocyclododecane (HBCD)	○	○	○		
	Butadiene styrene brominated copolymer [CASRN 1195978-93-8]					
Blowing Agent	Pentane					
	Cyclopentane					
	Isopentane					
Potential Residual Monomer	Styrene		●			
Specialty Additives	Disodium Octaborate Tetrahydrate		○			
Exposure Scenarios to Consider	• Human exposure during product use • Human and environment via environmental releases from product					

Qualitative exposure assessment	See the methodology used in the Key Concepts and Definitions section • Exposure to the butadiene styrene brominated copolymer may be considered negligible during product use due to the high molecular weight of the chemical. A data gap exists regarding the ability of this chemical to breakdown to smaller, more mobile chemicals over time. Exposure to this chemical and its process chemicals or degradation products is possible during other life cycle stages. • None of the other chemicals above met the screening criteria for negligible exposure.

Note:

● The chemical is identified on the hazard list indicated. No alternatives were identified for this chemical function.

○ The chemical is identified on the hazard list indicated. The chemical is not used in all regions, being phased-out, and/or alternative chemicals are available for this process.

‡ The chemicals flagged in this column are identified as Substances of Very High Concern (SVHC) for REACH, either banned unless authorised, candidate list, or prioritised for listing.

Source: Sources for Tables 2.7. to 2.10. (Poppendieck, Gong and Lawson, 2016; NCFI Polyurethanes, 2017; Henry Company, 2020; Naldzhiev, Mumovic and Strlic, 2020; UNEP, 2020c; Healthy Building Network, no date c)

Table 2.8. Chemicals that may be present in XPS insulation during use as installed

	Chemical Name	SVHC‡	SIN List	POP	ODS	High GWP
Flame Retardants	Hexabromocyclododecane (HBCD)	○	○	○		
	Butadiene styrene brominated copolymer [CASRN 1195978-93-8]					
Blowing Agent	HFC-134a					○
	HCFC-142b/22 blends[a]				○	○
	HFO-1234ze					
	CO2 and hydrocarbons such as isobutane					
Potential Residual Monomer	N/A					
Exposure Scenarios to Consider	• Human exposure during product use • Human and environment via environmental releases from product					
Qualitative exposure assessment	See the methodology used in the Key Concepts and Definitions section • Exposure to the butadiene styrene brominated copolymer may be considered negligible during product use due to the high molecular weight of the chemical. A data gap exists regarding the ability of this chemical to breakdown to smaller, more mobile chemicals over time. Exposure to this chemical and its process chemicals or degradation products is possible during other life cycle stages. • None of the other chemicals above met the screening criteria for negligible exposure.					

Note:

● The chemical is identified on the hazard list indicated. No alternatives were identified for this chemical function.

○ The chemical is identified on the hazard list indicated. The chemical is not used in all regions, being phased-out, and/or alternative chemicals are available for this process.

‡ The chemicals flagged in this column are identified as Substances of Very High Concern (SVHC) for REACH, either banned unless authorised, candidate list, or prioritised for listing.

a As of 2018 China was still reported to be using blends of HCFC-142b/22 (UNEP, 2018a). In 2020, medium and large enterprises in China were reported to be moving towards HFC and CO2-based blowing agents as HCFCs continue to be phased out there (UNEP, 2020c).

Source: Sources for Tables 2.7. to 2.10. (Poppendieck, Gong and Lawson, 2016; NCFI Polyurethanes, 2017; Henry Company, 2020; Naldzhiev, Mumovic and Strlic, 2020; UNEP, 2020c; Healthy Building Network, no date c)

Table 2.9. Chemicals that may be present in polyiso insulation during use as installed

	Chemical Name	SVHC‡	SIN List	POP	ODS	High GWP
Flame Retardants	Tris(2-chloroisopropyl) phosphate (TCPP)		○			
	Diethyl hydroxymethyl phosphonate (at this stage already reacted to be part of polymer chain, potentially present as residual only)					
Blowing Agent	Pentane					
	1-bromopropane		○			
Potential Residual Monomer	N/A					
Exposure Scenarios to Consider	• Human exposure during use • Human and environment via environmental releases from product					
Qualitative exposure assessment	See the methodology used in the Key Concepts and Definitions section • Exposure to diethyl hydroxymethyl phosphonate may be considered negligible during product use due to the fact that it is reacted into the polymer chain. A data gap exists regarding the ability of this reaction to reverse or for the chemical to breakdown to smaller, more mobile chemicals over time. Exposure to this chemical and its process chemicals or degradation products is possible during other life cycle stages. • None of the other chemicals above met the screening criteria for negligible exposure.					

Note:

● The chemical is identified on the hazard list indicated. No alternatives were identified for this chemical function.

○ The chemical is identified on the hazard list indicated. The chemical is not used in all regions, being phased-out, and/or alternative chemicals are available for this process.

‡ The chemicals flagged in this column are identified as Substances of Very High Concern (SVHC) for REACH, either banned unless authorised, candidate list, or prioritised for listing.

Source: Sources for Tables 2.7. to 2.10. (Poppendieck, Gong and Lawson, 2016; NCFI Polyurethanes, 2017; Henry Company, 2020; Naldzhiev, Mumovic and Strlic, 2020; UNEP, 2020c; Healthy Building Network, no date c)

Table 2.10. Chemicals that may be present in SPF insulation during use as installed

	Chemical Name	SVHC‡	SIN List	POP	ODS	High GWP
Flame Retardants	Tris(2-chloroisopropyl) phosphate (TCPP)		●			
Blowing Agent	HFC-245fa (closed-cell SPF)					●
	HCFC-141b (closed-cell SPF)[a]				○	○

	HFO-1233zd (closed-cell SPF)					
Potential Residuals and Byproducts	Dibutyltin dilaurate		○			
	1,4-Dioxane[b]		●			
	1,2-Dichloropropane[b]		●			
	1,2-Dichlorobenzene[b]		●			
Exposure Scenarios to Consider	• Direct human via product. • Human and environment via environmental releases from product					
Qualitative exposure assessment	See the methodology used in the Key Concepts and Definitions section. • None of the chemicals above met the screening criteria for negligible exposure.					

Note:

● The chemical is identified on the hazard list indicated. No alternatives were identified for this chemical function.

○ The chemical is identified on the hazard list indicated. The chemical is not used in all regions, being phased-out, and/or alternative chemicals are available for this process.

‡ The chemicals flagged in this column are identified as Substances of Very High Concern (SVHC) for REACH, either banned unless authorised, candidate list, or prioritised for listing.

a HCFCs continue to be phased out globally but are still used in spray foam applications in some regions (UNEP, 2020c).

b Some studies have considered emissions from SPF insulation over time. Those chemicals identified in literature that are not already included as content or potential residuals in the table are listed as potential byproducts if they are on one of the hazard lists identified (Poppendieck, Gong and Lawson, 2016; Naldzhiev, Mumovic and Strlic, 2020).

Source: Sources for Tables 2.7. to 2.10. (Poppendieck, Gong and Lawson, 2016; NCFI Polyurethanes, 2017; Henry Company, 2020; Naldzhiev, Mumovic and Strlic, 2020; UNEP, 2020c; Healthy Building Network, no date c)

2.4.3. Flame retardants

As noted above, plastic foam insulation almost always contains flame retardants in order to meet flammability standards. In cases where they can be avoided, that is preferred, employing the hierarchy of controls framework (see definition in Key Concepts and Definitions section) to remove the hazard as a first priority. When a flame retardant must be used, the specific flame retardant choice can impact toxicity and potential for exposures.

As noted above, EPS and XPS have historically used the flame retardant HBCD, which is an SVHC and POP. HBCD has been identified in indoor environments and in people (Dedeo and Drake, 2017). Some regions may still use HBCD in insulation, but many have transitioned to a brominated polymeric flame retardant, butadiene styrene brominated copolymer. The human health and ecotoxicity hazards of this flame retardant are lower than for HBCD (US EPA, 2014).

SPF and polyiso insulation commonly use tris(2-chloroisopropyl) phosphate (TCPP) as a flame retardant. TCPP is an organophosphate flame retardant that has been identified in indoor air and dust (Dedeo and Drake, 2017; Petty et al., 2017). It is on the SIN List, and the European Chemicals Agency (ECHA) has recommended TCPP for restriction in flexible polyurethane foams in childcare articles and residential upholstered furniture (ECHA, 2018).

Flame retardants like TCPP and HBCD are not chemically bonded to the insulation. Consequently, they can leach out of the product during use, creating potential for users to be exposed via dermal contact, inhalation, or ingestion of contaminated food, water, or dust (Babrauskas et al., 2012; US EPA, 2014). Where the insulation is installed and whether barriers such as drywall or plaster are installed over insulation can impact the exposure potential for building occupants. Once these persistent chemicals leach from products, however, they can enter the environment and spread more broadly.

Polymeric flame retardants, as larger chain chemicals, are less likely to migrate from products during use and expose individuals during the product life. Similarly, reactive flame retardants become part of the polymer chain during the manufacturing process and are also less likely to be emitted from a product during use and subsequently expose building occupants. Innovation has led to the availability of a reactive, non-halogenated flame retardant option that is currently used in some polyiso products and is advertised for use in polyurethane insulation (Symes and Leifer, 2017). Public full chemical hazard assessments for this or other non-halogenated flame retardant options should be pursued to ensure they are inherently low hazard. Resources are increasingly available to provide information on potential alternative additives (OECD, 2021; ChemSec, no date a; ECHA, no date c; Product Selector, no date). Resources such as the OECD Substitution Toolbox can be used to identify tools for substitution and alternatives assessment (OECD, no date c). Product manufacturers can choose safer alternatives as they take steps toward inherently low hazard at all life cycle stages.

2.4.4. Blowing agents

Blowing agents can also have impacts during product use. In North America and elsewhere, HFC blowing agents with high GWP are still used in XPS and SPF insulation. HFOs, which do not have high GWP, are replacing HFCs in these applications. These blowing agents are expected to off-gas from the product over its entire lifecycle, including during its use phase (Owens Corning, 2019). On the other hand, EPS and polyiso insulation commonly use pentanes, which do not have a high global warming potential, as blowing agents.

2.4.5. Other emissions

Besides potential emissions of flame retardants and blowing agents during product use, a range of chemicals have been measured in emissions from various SPF products. A National Institute of Standards and Technology (NIST) report detected more than 80 different chemicals emitted from one SPF sample, including TCPP and amine catalysts (Poppendieck, Gong and Lawson, 2016). Not all of the chemicals emitted were identified. They may include intentional content, impurities, or reaction products. Some emissions may occur primarily during the month or less following installation. Others may continue over longer periods of time (Naldzhiev, Mumovic and Strlic, 2020). Several chemicals identified in SPF emissions are on the SIN List. Installation conditions and the closed cell or open cell nature of the foam may impact the chemicals emitted and the rate of emission.

EPS is processed at a lower temperature than XPS, so is more likely to have residual styrene monomer in the finished product that may off gas during the use phase. Broad emission testing for EPS, XPS, and polyiso was not identified for this case study and represents a data gap in the comparison.

2.4.6. Non-standard use-phase conditions

Additional use-phase considerations include impacts during disaster scenarios, such as fires. Plastic insulation materials, as most construction products, burn and release toxic chemicals during combustion. This can produce dangerous conditions for residents (Purser, 2018). It can also contribute to firefighters' exposure. Consideration of materials that can minimise hazardous exposures for first responders and residents during fires should be part of the design considerations for sustainable plastics.

2.4.7. Key considerations - product use

- Design systems holistically and use life-cycle thinking
    - Is there an engagement plan to educate workers and customers on different installation options and the impact trade-offs of each option?
    - Is there a process in place to consider, test, develop, and encourage innovative installation technologies or products as a service approaches?
    - Are measures in place to track and report key sustainability measures? For example, survey installation workers on injuries and health concerns.
- Maximise resource efficiency.
    - Were different product designs and installation methods considered and compared by resource use? For example, consider installation methods that reduce waste during installation.
    - Are current installers measuring and reporting product waste during installation? Are there goals to reduce product waste during installation?
- Eliminate and minimise hazards and pollution
    - Were different product designs and installation methods considered and compared based on ability to minimise hazardous substance use and pollution?

2.4.8. Example Trade-offs - product use

During the use phase as installed, EPS and XPS insulation made with the polymeric brominated flame retardant and polyiso made with the reactive non-halogenated flame retardant are expected to be of lower hazard and less exposure potential than products that contain flame retardants like HBCD and TCPP. Chemicals that are inherently low hazard throughout their life cycle should be considered as alternatives and should be fully assessed for their hazards and reviewed for potential life cycle trade-offs.

SPF insulation is effectively manufactured on site as it is installed. This allows for the insulation to form to the surroundings in which it is installed, and can provide air sealing as well as insulative properties. However, there is significant potential for worker exposure to hazardous substances and potential for variations in the conditions that impact the finished product performance and emissions. For example, several variables can affect performance, such as proper mix ratio, ambient temperature and humidity, substrate cleanliness, thickness of a single pass, and overall installed thickness. Problems such as cracks, blowholes in the foam, shrinkage away from the framing, or even scorching within the foam due to excessive heat given off by the chemical reaction have all been observed (Knowles, 2010). Cracks, holes, or gaps formed during installation may be difficult to detect and can compromise the R-value and air-sealing properties if they are not remedied (Kaye, 2012; ‘Foam Fails Reason #5: Excessive Shrinkage’, 2014). There can also be significant nonuniformity in an application (Poppendieck, Gong and Lawson, 2016). Improper installation can lead to gummy or brittle foam, as well as lingering odours, which are both performance and health concerns (Knowles, 2010; CPSC, 2012). While protective equipment is prescribed for spray foam installers, the hierarchy of controls framework identifies this as the least effective way to protect workers. Elimination or substitution are the most effective method of protection (see Key Concepts section).

2.5. End of Life

The European Union's Waste Framework Directive is an example of a framework that can be used to design products that meet the sustainable plastics goals by maximising resource efficiency. It defines a waste hierarchy that prioritises how waste should be dealt with at the end of life to minimise its impact on the environment. In order of decreasing priority the hierarchy includes prevention, reuse, recycling, other recovery (e.g. energy recovery), and disposal (Directive 2008/98/EC, 2018).

Most often plastic insulation is landfilled or incinerated at the end of the product's life (SPFA, 2018; Potrykus et al., 2019; PIMA, 2020; US EPA, 2020). For example, in Europe, about 53% of EPS construction waste is incinerated for energy recovery, about 40% is landfilled or incinerated without energy recovery, and only 7.5% of EPS waste is recycled (PolyStyreneLoop Cooperative, no date). Because polyiso and SPF insulations are thermoset materials, they are inherently more challenging to recycle than thermoplastic materials like polystyrene (ChemistryViews.org, 2019; Spray Polyurethane Foam Alliance, no date). This can be a consideration when choosing the polymeric material to use in design of an insulation product. Where in the building the product is used may also impact what happens at the end of product life. For example, buried material may remain in the environment after use (ECHA, 2008).

Regardless of where materials go at their end of life, removal of materials or demolition of buildings can expose workers to hazardous substances and release hazardous substances into the broader environment through dust and debris (UNEP, 2015). Recycling and disposal can also release hazardous substances into the environment, which can impact communities neighbouring these facilities and the broader environment. From a sustainable design perspective, eliminating hazardous substances in products supports safe reclamation and reuse or recycling. Content transparency and labelling can help to separate products without hazardous content for reuse or mechanical recycling.

2.5.1. Landfill

Because plastic foam insulation is designed to last over 50 years, at the end of its life it can contain legacy chemicals that have since been phased out of new products. For example, most of the EPS and XPS in buildings currently contains HBCD (US EPA, 2020). Likewise, older formulations of XPS and SPF insulation may retain a small percentage of their CFC and HCFC blowing agents, which have both high GWP and are ozone depleting substances (ODS). While options exist to collect and destroy these blowing agents, most foam insulation is likely to be landfilled, where without controls, the remaining blowing agent in the product can be released (American Carbon Registry (ACR), 2017; US EPA, 2018).

As with EPS and XPS, polyiso and SPF insulations are also most often landfilled (SPFA, 2018; PIMA, 2020). Consequently, disposal of each type of insulation has the potential to introduce HBCD or TCPP into the environment. Numerous leaching studies have documented pathways for potential exposure to HBCD from EPS and XPS (US EPA, 2020). Fires in landfills can also lead to chemical releases. Uncontrolled burning of halogenated flame retardants, including HBCD, the brominated polymeric flame retardant, and TCPP, may produce as combustion by-products such as polybrominated dibenzo-p-dioxins and dibenzofurans (US EPA, 2014; Charbonnet, Weber and Blum, 2020). Plastic insulation that uses alternatives may have fewer hazardous releases upon landfilling, but more data on if and how these materials break down is needed.

2.5.2. Incineration

EPS and XPS

Some polystyrene insulation is incinerated at the end of life in some regions. Incineration can release styrene monomer (Styrene, Styrene-7,8-oxide, and Quinoline, 2019). In properly functioning incinerators, styrene should be largely destroyed and HBCD is destroyed with very high efficiency (Mark et al., 2015). If not functioning properly, emissions of hazardous byproducts like polybrominated dibenzodioxins and polybrominated dibenzofurans can occur from brominated flame retardants (Charbonnet, Weber and Blum, 2020; ECHA, 2008; US EPA, 2014).

Polyiso and SPF

Some polyisocyanurate or SPF insulation may be incinerated as part of municipal solid waste. Burning polyurethane can release toxic substances such as hydrogen cyanide (Guo et al., 2017). Burning halogenated flame retardants like TCPP can lead to the generation of halogenated dioxins and furans (US EPA, 2014; Petty et al., 2017). Modern incinerators have equipment to capture toxic pollutants that are generated, but only if the facilities are regularly maintained and operating properly (World Energy Council, 2016; Tait et al., 2020).

2.5.3. Recycling

Recycling of plastics is an important end of life pathway to support a circular economy. Plastics can be recycled through either a chemical or a mechanical process, both having limitations or drawbacks. Chemical recycling allows separation of additives and returns polymers to their original polymer or monomer form. Mechanical recycling is the less expensive option, but it does not allow for the separation of additives.

While some insulation is recyclable, hazardous additives make products more challenging to recycle if those additives need to be removed to make the material a feasible recycled feedstock.

EPS and XPS

HBCD in existing building insulation presents an occupational exposure concern during removal of EPS and XPS insulation. In 2020, a U.S. EPA risk evaluation determined that HBCD presents an unreasonable risk for six conditions of use, including during removal and recycling of EPS and XPS foam panels. The report determined that demolition teams are at risk for thyroid hormone disruption affecting offspring and developmental toxicity due to acute and chronic inhalation exposure (US EPA, 2020).

In 2015 The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal identified EPS and XPS insulation boards as forming the majority of HBCD wastes.[4] Management of waste containing HBCD is addressed under the Basel Convention, which impacts the movement of hazardous waste between countries (UNEP, 2015). If EPS or XPS insulation containing HBCD are identified as hazardous waste, then they would be subject to the prior informed consent (PIC).[5] It should be noted, however, that while EPS and XPS insulation boards containing HBCD could be identified as hazardous waste based on the language of the Basel Convention, it is possible that they may not be classified as hazardous waste if national tests conclude that they need not be (UNEP, 2015; PlasticsEurope et al., 2016). Regardless of how waste is classified, however, the Convention requires the environmentally sound management (ESM) of wastes. Separation of older EPS and XPS containing HBCD from newer boards by inexpensive screening techniques like X-ray fluorescence (XRF) could be more challenging if the newer boards contain other brominated flame retardants. XRF can determine whether or not these boards contain bromine, but more costly analytical techniques are required to determine whether or not the bromine is from HBCD. See the Policy Considerations section for a more in-depth discussion of additional measures that can be used in tandem with the policies measures that support the Basel Convention to promote the development of sustainable plastics.

Polystyrene can be recycled, and because it is thermoplastic, it can be moulded into new products. Inclusion of flame retardants in polystyrene insulation may limit the applications into which it could be recycled. No formal programs for recycling XPS insulation exist in the U.S. Likewise, in Europe landfilling and incineration are the most likely end of life options for XPS, with no reported post-consumer recycling (EXIBA, 2019; Potrykus et al., 2019). There are formal programs in North America for post-consumer EPS materials, but this is primarily for EPS packing, and most EPS insulation is expected to be landfilled (EPS Industry Alliance, 2017). Some EPS insulation may be incorporated into other building materials, for example, as light aggregates in concrete (McAuley and Patterson, 2016). Overall recycling rates for plastic insulation remain low in the EU (Potrykus et al., 2019), but there are also some programs for recycling polystyrene insulation. For example, in Germany polystyrene insulation is collected on a national level (US EPA, 2014). In 2016, 98% of the post-consumer EPS and XPS waste there was recovered for recycling or incineration (Plasteurope.com, 2017).

The polystyrene chemical recycling facility in Canada uses cymene as the solvent (Lauzon, 2018). This is not a SVHC, SIN List chemical, or POP. The facility is reportedly focused on recycling household polystyrene, though the process can remove HBCD to below the detection limit, and reports a capacity to process 600 tonnes per year (Lauzon, 2018; Plasteurope.com, 2018; Polystyvert, no date). The chemical recycling facility under development in the Netherlands, PolyStyreneLoop, uses a proprietary solvent purification process to recycle XPS and EPS insulation. The specific solvent used is not identified, although identified as “not dangerous according to GHS” (PolyStryeneLoop Cooperative Website, no date). The process recovers the polystyrene, removing the HBCD and recycling the bromine (EXIBA, 2020; Hann and Connock, 2020; PolyStyreneLoop Cooperative, no date). The resulting polystyrene contains some level of HBCD (<100 ppm) and the solvent used in processing as contaminants, as well as carbon black and graphite impurities (Hann and Connock, 2020). The current facility will have capacity to recycle 3,000 tons of EPS and XPS insulation annually, meaning, in the near term, most EPS and XPS insulation waste will not be recycled.

Polyiso and SPF

As noted above, polyiso and SPF are most often landfilled. In addition, because SPF insulation is foamed in place, it adheres to the materials around it, such as wood studs, and can be difficult to separate from them, potentially making it difficult to reuse or recycle these materials.

Rigid polyurethane foam can potentially be ground into a powder and used as a filler in a new polyurethane product or in other products such as concrete (Yang et al., 2012). It is not clear whether this is currently done in practice.

Chemical recycling of polyurethane materials is possible through chemical depolymerisation, but proposed processes have not typically advanced beyond lab scale. One company is reportedly looking to expand their work in depolymerisation of flexible polyurethane into rigid polyurethane foams using glycolysis (Hann and Connock, 2020). Information was not available as to whether this could be applied to insulation products. New research programs, such as Europe’s “PUReSmart,” are also looking into ways to recover used polyurethane products generally and develop sorting technologies and chemical recycling to turn used polyurethane into raw materials for new products (ChemistryViews.org, 2019).

2.5.4. Reuse

EPS, XPS, and Polyiso

Foam board insulation has a long product life and can be salvaged and reused. Though this is not currently done at a large scale, there are some notable examples, such as during the re-roofing of the Dallas Fort Worth International airport, where most of the 17-year-old XPS insulation was recovered and reused (US EPA, 2014, 2020). Because of the historic use of HBCD, reuse of older EPS and XPS could lead to continued circulation of known hazardous chemical. Similarly, reuse of polyiso can cause continued exposure to TCPP. If products are designed to be inherently low hazard, and are identified as such, reuse becomes a greater option in the future.

SPF

Spray foam insulation is unlikely to be reused. Because it is foamed in place, it can stick to the surrounding materials, making separation difficult, and the irregular shape limits how the material could be used.

Table 2.11. End of Life Considerations

	EPS	XPS	Polyiso	SPF
Reuse Possible	✓	✓	✓	
Chemical Recycling available	✓	✓	✓*	✓*
Mechanical Recycling available	✓	✓*	✓*	✓*
Closed-loop process available & in place	Under development	Under development		
Legacy chemical concerns to consider in recycling operations	HBCD	HBCD, Blowing Agents (ODS, High GWP)	TCPP	TCPP, Dibutyltin dilaurate, Blowing Agents (ODS, High GWP)
Incineration	✓	✓	✓	✓
Landfilled	✓	✓	✓	✓
Chemical concerns from off-gassing, leaching, and/or burning to address	HBCD, Dioxins,[a] Furans[a]	HBCD, Blowing Agents (ODS, High GWP), Dioxins,[a] Furans[a]	TCPP, Dioxins,[a] Furans[a]	TCPP, Dibutyltin dilaurate, Blowing Agents (ODS, High GWP), Dioxins,[a] Furans[a]

Note:
* Theoretically possible, but no current large scale examples of this process were identified.
a These chemical groups are included because they contain numerous CASRNs identified as SVHCs, that are present on the SIN List, or that are identified as POPs under the Stockholm Convention.

2.5.5. Key considerations - end of life

- Design systems holistically and use life-cycle thinking
    - Are manufacturer take-back programs in place? Has a study been completed to understand regional gaps and opportunities in infrastructure to support manufacturer take-back programs?

    - Is there a process in place to consider, test, develop, and encourage innovative end of life solutions?
    - Are measures in place to track the end of life of plastic insulation? Are there goals to increase reuse and recycling and reduce incineration, landfill, and leakage?
- Maximise resource efficiency
    - Have different product designs been considered and compared by end of life options that reduce waste? For example, those that facilitate product disassembly and recycling.
    - Are the current product's end of life options known for each region? Are there regionally specific programs in place to increase reuse and recycling and reduce incineration, landfill, and leakage?
- Eliminate and minimise hazards and pollution
    - Were different product end of life options considered and compared based on ability to minimise release of hazardous substances and pollution?
    - Are there regional specific programs in place to minimise release of hazardous substances and pollution at the end of the product's life?

2.5.6. Example Trade-offs - end of life

Landfilling and incineration are not consistent with a sustainable materials management system and should not be considered options for future sustainable plastic product development. This case study does not include a complete review of potential emissions for these end of life scenarios. More complete information would be needed to compare alternative plastics for these two end of life scenarios. Reuse of plastic board insulation can be a sustainable option if the insulation does not contain hazardous substances that would expose building occupants and can be identified as such through content transparency and labelling. Mechanical or chemical recycling offers an opportunity for sustainability, but it comes with many challenges and trade-offs and is not currently widely adopted for insulation products. If hazardous additives are present in products, recycling workers can be exposed and chemicals released into the broader environment when materials are mechanically recycled. Where chemical additives are known and of low hazard, mechanical recycling is typically the most economically feasible option. Because polystyrene is thermoplastic, it can be mechanically recycled, melted, and moulded into new products. Polyurethane and polyisocyanurate, however, are thermoset materials. These materials could be mechanically recycled by grinding them up into fillers, but cannot be mechanically recycled as the base polymer into new insulation. In all cases, workers collecting and recycling plastic foam insulation may be exposed to hazardous additives such as flame retardants, and the presence of flame retardants is likely to limit possible applications for the recycled insulation materials. Transporting materials long distances for recycling can lead to additional life cycle impacts that would need to be considered when reviewing trade-offs of mechanical recycling. In the design process, using inherently low hazard additives and mechanically recyclable plastics, along with programs to develop the necessary infrastructure, can foster a closed-loop system.

Chemical recycling can help maximise resource efficiency by keeping materials out of landfills and has the potential to generate useful monomer or polymer feedstocks. It can minimise hazard and pollution by avoiding chemical emissions associated with the production of virgin materials and can remove legacy hazardous substances that may otherwise enter the environment if the product were to be landfilled. There are trade-offs in terms of energy required for transportation of the materials and for the chemical recycling process (Hann and Connock, 2020). Some chemical recycling processes also utilise hazardous process chemicals.

Notes

[1] An estimated 79% of the world's chlor-alkali capacity is based on PFAS membranes or diaphragms, 18% on asbestos diaphragms, and 3% on mercury cells. Production by asbestos technology is heavily concentrated in the United States. As of 2018, in North and South America 8 of the 12 largest plants in operation (an estimated 41% of chlor-alkali capacity) still used asbestos diaphragm technology and 8 plants (an estimated 4% of chlor-alkali capacity) used mercury cells. In Europe these two technologies are less common due to phase-out of these technologies, but Germany has one large plant that still uses asbestos diaphragms and two plants that use mercury cells. In Asia, an estimated 94% of chlorine is produced using PFAS-coated membranes, although several still operate using asbestos diaphragms. No major chlorine producers in Africa use mercury cell or asbestos diaphragm technology.

[2] SPF insulation is a two-component system that is mixed and reacted on site as applied to generate the foam. The product manufacture consists primarily of blending the ingredients into A-side and B-side components. The A-side is composed primarily of MDI and pMDI. The B-side contains the polyols, flame retardant(s), blowing agent(s), catalysts, and other additives.

[3] Full consideration of the global warming impacts of products throughout their life, including production emissions and energy savings, is outside the scope of this case study but is an important consideration. That information can be used to supplement the chemical hazard analysis.

[4] The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal is designed to address hazardous substances that end up in waste streams and to promote environmentally sound recycling on an international scale. It defines hazardous wastes as "Wastes that belong to any category contained in Annex I, unless they do not possess any of the characteristics contained in Annex III." Annex I defines the categories of wastes that are controlled, and Annex III defines the characteristics that these materials would need to have to be characterised as hazardous. The Convention also states that wastes can be considered hazardous if they do not meet the above criteria, but are "defined as, or are considered to be, hazardous wastes by the domestic legislation of the Party of export, import or transit."

[5] PIC requires that the country exporting the waste must provide the importing country with detailed information on the intended movement. The movement of the materials may only proceed when all countries involved have given their written consent. Transboundary movement of relevant hazardous and other wastes is only allowed if the state of export does not have the technical capacity and the necessary facilities, capacity or suitable disposal sites in order to dispose of the wastes in question in an environmentally sound manner, or the wastes in question are required as raw materials for recycling or recovery industries in the State of import; or the transboundary movement in question is in accordance with other criteria decided by the Parties. In all cases, the Convention requires that the standard of environmentally sound management of hazardous wastes or other wastes is met.

3. Policy considerations

This case study has used plastic insulation as an example to identify opportunities for improvement toward sustainable plastics from a chemicals perspective. In the introduction, design principles are used to generate key considerations needed to work towards sustainable plastics goals (see Figure 2.2). In this section, those same sustainable plastic goals are used to define policy instruments that can encourage and reward work towards sustainability outcomes.

3.1. Broad Regulations on Chemical Content

Regulations restricting chemical content in a finished product not only can eliminate hazards at all phases of production, but also have potential to give a product a commercial afterlife. In order for these regulations to be effective at promoting the development and use of sustainable plastics, however, they must have a wide reach both in product type coverage and, when appropriate, chemical class coverage.

The global phase-out of HBCD in polystyrene insulation is an example of how regulations with a wide reach can be effective. Moreover, it demonstrates the benefit of considering a broad spectrum of products in regulatory efforts. HBCD was added to Annex A of the Stockholm Convention in 2013. At that time, HBCD was still widely used in both EPS and XPS insulation. Under the Convention, countries could apply for an exemption on the use of HBCD in EPS and XPS in buildings (UNEP, 2018b). Currently, only China has an active exemption, which gave them an additional five-year period to transition away from the production and use of HBCD in EPS and XPS, although the exemption is set to expire in 2021 (UNEP, no date b). In accordance with the Stockholm Convention, regions have taken action to restrict and prohibit the use of HBCD in all sectors. For instance, HBCD was sunset in the EU in 2015 (ECHA, no date b). In India, although the government has not updated its National Implementation Plan since 2011, in 2018 they passed legislation prohibiting the manufacture, trade, use, import, and export of seven POPs including HBCD (Ministry of Environment, Forest and Climate Change, 2018). Furthermore, the effects of widespread national bans on HBCD have been felt globally beyond Stockholm Convention signatories. Although the U.S. is not a signatory of the Convention, as a result of global restrictions on HBCD it has phased away from its use as well. Industry representatives in the U.S. indicate that HBCD is no longer manufactured there, and use of stockpiles and exportation was completed in 2017 (US EPA, 2020). One variable that has likely supported this transition is the availability of butadiene styrene brominated copolymer as an alternative that was considered both technically and economically feasible early on in the transition process (Corden et al., 2014).

As noted above, butadiene styrene brominated copolymer offers comparable performance, and its human health and ecotoxicity hazards are lower than those of HBCD (Corden et al., 2014; US EPA, 2014). However, it is environmentally persistent and its long-term behaviour is still unknown (US EPA, 2014).

In order to ensure that regulations are protective of human health and to protect products from likely future regulations application of a class-based approach described in the key concepts section of this case study should be considered. A class-based approach recommends that if known hazards are sufficient to justify restrictions for one member of a family or class of chemicals, then the entire class should be considered for restrictions unless proven otherwise. The burden of proof for such chemicals should be placed on proving low hazard and safety of the exceptions, rather than proving hazard and potential harm. Existing examples of the class-based approach in policy include the U.S. EPA ban on polychlorinated biphenyls (PCBs) and the European Union directive limiting total perfluoroalkyl substances (PFAS) in drinking water (US EPA, 1979; Directive (EU) 2020/2184, 2020).

In the case of insulation, a class-based approach to regulatory efforts has been instrumental in the phasedown of several classes of chemicals, including CFCs (UNEP, 1987). The Montreal Protocol has driven the transition from CFCs and HCFCs to HFCs in many sectors, including insulation, given that the latter have no ozone-depletion potential. They do, however, have high GWP. To address this, the Montreal Protocol was amended in 2016. Under the Kigali amendment, countries are required to phase down the use of HFCs at different rates that will drastically cut HFC emissions by the middle of the century (United Nations, 2016).

The Montreal Protocol has already led to significant reductions in the use of CFCs, HCFCs, and HFCs. Nevertheless, transitioning to new chemicals can lead to technological and financial setbacks. While the cost of HCFCs continues to rise, HFOs are still more expensive than HFCs (UNEP, 2020c). In the U.S., weak support for the HFC phase-out at a national level has created additional hurdles. U.S. EPA regulations that would have prohibited the use of HFCs in XPS insulation by 2021 have been overturned in Federal court rulings. Several states in the U.S. have moved forward with their own regulations based on the previous EPA timeline, but industry associations are litigating these regulations, advocating for a more unified implementation of the regulations, citing concerns over potential supply chain issues resulting from inconsistent requirements in different states (Garry, 2019; Taylor, 2020).

3.2. Emissions Inventories and Regulations

Emissions inventories can be useful in identifying major sources of pollution and can be helpful in setting targets for reducing environmental emissions of hazardous substances. The Batumi Action for Cleaner Air (BACA) initiative was established to help policymakers implement decisions to improve air quality in 27 countries (UNECE, 2016, 2018). One goal of the initiative is the establishment of systematic, comparable and transparent monitoring activities and emissions inventories. One approach to reducing these emissions is the development of engineering controls that mitigate the release of hazardous substances into the environment. The development of manufacturing processes that minimise the use of hazardous inputs, intermediates, products, and by-products (i.e. those that use fewer hazards chemicals at all stages of production) can further help reduce the release of these chemicals into the environment. For example, when manufacturers in the U.S. transitioned away from the use of formaldehyde-based binders in fiberglass batt insulation, the U.S. EPA Toxics Release Inventory data revealed a sharp decline in environmental releases of formaldehyde from these facilities in the decade that followed (Vallette, 2015). In this regard, emissions inventories can be a means to track progress in the reduction of environmental emissions achieved by using chemical processes that are inherently low hazard.

3.3. Material Disclosure Incentives/Requirements

Policies requiring or incentivising material disclosure can also have widespread effects. Like regulations on chemical content, they can incentivise the creation of products that are inherently low hazard and can also support a commercial afterlife for products. Material disclosure, like that found in the database on Substances of Concern In articles as such or in complex objects (Products) (SCIP) in the EU enables SVHCs to be identified in whole products at various stages of their lifecycle (ECHA, no date d). This level of transparency not only can help product designers eliminate hazardous substances from products, but also can give waste operators the ability to segregate products based on the presence or absence of SVHCs and identify potentially problematic waste streams.

Policies requiring full product content disclosure standardise materials transparency across an industry. For example, in the cleaning product sector, California now requires cleaning products to disclose all ingredients on their labels (S.B. 258, 2017). Most product content disclosure today has been driven by either cost savings or market advantage. Data from the electronics sector have demonstrated that full material disclosure incurred more up-front costs, but over time led to a net cost savings as changing regulations or client specifications could be confirmed immediately with fewer compliance requests needed from suppliers (Wu, 2018). In the building product sector, green building standards such as LEED sparked materials disclosure by adding a building materials disclosure and optimisation credit to LEED V4.0. Now product disclosure is driven, in part, by firm-wide policies. As of 2020, approximately 100 architecture and design firms have signed a letter to building product manufacturers stating they will prefer, select, and specify products with content disclosure (Materials Pledge Signatories, 2020).

Regardless of the driving forces, extending the materials disclosure principle to full product content disclosures such as Health Product Declarations and Declare Labels, as described in the key concepts section above, has the added benefit of both identifying known hazardous substances as well as those not identified as hazardous, which may not yet be fully studied. Such disclosure has clear benefits from a circularity perspective. Whether or not the content has known hazards at the time of manufacture, product content disclosures enable proper handling at the end of life when additional hazard information may be available. Thus, transparency creates greater opportunity for reuse or recycling. Furthermore, this disclosure can also help provide a broader understanding of the chemicals most often used in products and identify priorities for full chemical hazard assessments.

3.4. End-of-life Policies

Creating a plastic with inherently low hazards and a commercial afterlife does not guarantee that it will be reused or recycled. The proliferation of plastics use and often poor end-of-life waste management have helped to generate widespread plastic pollution. Strong end-of-life policies can help ensure that materials that can be recycled are recycled. They can also limit the generation of waste, and ensure that waste-derived materials without hazardous content are incorporated into new products. Thus, financing efficient collection and management schemes should be prioritised.

The new plastic waste amendments to the Basel Convention could potentially drive the development of policies that aim to separate plastic waste contaminated with legacy chemicals from waste that is not. (UNEP, 2019a, 2020a). Because the Basel Convention is aimed at reducing the movement and disposal of hazardous waste across international boundaries, domestic policies aimed at reducing hazardous waste should reflect the priorities outlined in the Convention as well.

Policies promoting and rewarding aggressive collection and management schemes can help ensure that plastic that can be recycled is recycled. In the building materials sector, government policies that promote construction and demolition debris recovery can help nations and communities move toward zero waste and promote the use of sustainable plastics. For instance, the U.S. city of San Francisco has an ordinance requiring all construction and demolition debris to be reused or recycled (SF Environment, 2011). Such policies do not ensure that materials are inherently low hazard. In order for them to be effective from a sustainable plastics perspective, they must be combined with strong policies limiting hazardous content and promoting product content disclosure. Sweden, for example, has taken steps in this direction by requiring inventories of hazardous wastes in buildings; these hazardous wastes must then be separated from other waste and collected before demolition. Likewise, other Nordic countries have regulations requiring inventories and reporting of hazardous wastes prior to demolition to varying degrees (Wahlström et al., 2019). While the benefit of combining aggressive collection and management schemes with policies limiting hazardous content and those requiring product content disclosure may not be felt immediately, combining them may be seen as a long-term goal of sustainable materials management.

Effective waste management policies are also key in efforts to generate zero waste. Closed-loop recycling programs aim both to give products a commercial afterlife and to generate no waste, but also must ensure that toxic chemicals are not passed on as post-consumer content is incorporated into new materials. This study did not identify any significant take-back programs for plastic insulation materials. The PolyStyreneLoop project noted above, however, indicates that closed-loop recycling of polystyrene insulation could be further developed to divert more polystyrene insulation from landfills and incinerators. The project, headed by a non-profit based in the Netherlands, began in 2017 and will conclude in 2023. It is designed to create a facility that can recycle 3000 tons of EPS and XPS construction waste each year through a process that removes most of the HBCD and recycles the bromine (PolyStyreneLoop Cooperative, no date).

An additional pathway to reduce waste is extended producer responsibility (EPR). OECD defines EPR as “a policy approach under which producers are given a significant responsibility – financial and/or physical – for the treatment or disposal of post-consumer products” (OECD, no date b). EPR programs, such as those implemented in Korea, Japan, and parts of Europe, have been shown to increase recycling and reduce waste; these programs may also help promote the development of products that are designed for takeback, disassembly, and reuse or recycling (OECD, 2006). The Basel Convention offers a number of resources related to the environmentally sound management of plastic waste geared towards helping parties to the convention comply with the plastic waste amendment adopted in2019 (UNEP, no date a). These guidelines include a manual providing stakeholders with guidance on the implementation of EPR that includes key elements to be considered and strategies to formulate policies, along with practical examples of EPR programs (UNEP, 2019b).

3.5. Using the Full Diversity of Policy Instruments

Table 3.1. summarises the policy considerations outlined above, and suggests which sustainable plastics goals each is likely to impact. While many of the actions described here will be familiar to policymakers, no one policy is likely to address every element required to create more sustainable plastics. In order to fully support the development of sustainable plastics, a diverse set of policy instruments should be adopted and tested to ensure that they align to produce the desired results. By vetting policies against the sustainable plastics goals, policymakers can begin to identify where existing policies need to be supplemented. Careful analysis should be conducted to determine whether or not policies are influencing design considerations that help achieve these goals. Furthermore, policymakers should work to actively identify roadblocks that exist to accomplishing these intended goals.

Sometimes these roadblocks are other policies. The OECD recently held a workshop where case-studies on real-world examples of conflicting policies hindering progress on chemicals and waste management and possible solutions (OECD, 2020). For example, regulations in Colombia limiting the transport of hazardous substances to another company for reuse leads to more hazardous substances being landfilled. Solutions include alignment of legislation that promotes a circular economy and policies that regulate hazardous substances.

A vital element of implementing an array of policies focused on these sustainable plastics goals is information sharing. The Basel Convention Partnership on Plastic Waste has identified a number of activities that aim to address (1) plastic waste prevention and minimisation, (2) plastic waste collection, recycling, and other recovery including financing and related markets, (3) transboundary movements of plastic waste, and (4) outreach, education, and awareness-raising (UNEP, 2020b). Aggressive plans to collect and analyse information on the degree to which chemical regulations, product content disclosure, and end of life financing schemes like EPR contribute to the development of sustainable materials over time can support their efforts. These efforts, in turn, have potential to support the further development of sustainable plastics.

Table 3.1. Policy Considerations to Support Sustainable Plastics

	Sustainable Plastics Goals			
Examples of Policy Instruments	Inherently low hazard	Commercial afterlife	Generate no waste	Rapidly renewable resources or waste-derived materials
		Chemical Regulations		
Broad regulations on chemical content	✓	✓		
Material Disclosure Incentives/Requirements				
Emissions inventories and regulations	✓		✓	
Materials disclosure incentives/requirements (e.g. SCIP database)	✓	✓		
		End of Life		
Subsidisation of recycling programs and infrastructure[a]	✓	✓	✓	
Construction and demolition waste collection programs		✓	✓	
Extended producer responsibility (EPR)	✓	✓	✓	
Closed-loop recycling programs		✓	✓	✓
Controlling movement/disposal of hazardous wastes (e.g. Basel Convention)				✓

Note:

a Subsidisation of recycling programs and infrastructure can help ensure materials are inherently low in hazard when used in combination with pre-demolition audits requiring materials containing hazardous substances to be identified and separated from other waste prior to demolition (European Commission, 2018; Wahlström et al., 2019).

4. Sustainable plastic insulation criteria

The final goal of this case study is to identify key criteria that should be considered regarding the potential environmental and human health impacts due to chemical selection considerations. Using the Sustainable Plastic Goals outlined above and informed by the data collected on the example plastic insulation products, EPS, XPS, polyiso, and SPF, a set of criteria was developed. Below is a summary of important criteria to consider when designing or selecting plastic insulation to reduce the impacts on human health and the environment at each life cycle stage of the product.

Sustainable plastics enhance human and environmental health and safety across the entire product life cycle. They:

Are inherently low hazard:

- Hazardous substances, especially those with potential for exposure to workers, community, users and environmental receptors, are eliminated at all life cycle stages including
    - Base polymer and source materials:
        - The base polymer chosen uses the least hazardous chemicals in the manufacturing and produces the least hazardous production emissions.
        - Within that base polymer, the manufacturing route chosen uses the least hazardous chemicals.
        - The base polymer chosen minimises the need for additives, simplifying the makeup of the final product.
        - Recycled feedstocks are used and are from known sources and tested for common hazardous content to avoid introducing hazardous content into new products.
    - Product manufacturing including additives/additive life cycle:
        - The product uses the fewest number of additives possible.
        - Additives that are used are fully assessed for hazards and are the least hazardous available.
        - The product is designed with circularity in mind, considering potential future regulations and emerging chemicals of concern that could impact the recyclability/reusability of the product at the end of life.
    - During installation and use:
        - When not all chemicals are inherently low hazard, chemical reactions take place in controlled manufacturing environments to reduce potential exposures and do not react on site.
        - The installation process avoids the use of hazardous accessory products (such as hazardous adhesives). If accessories are needed for installation, they have been fully disclosed, fully assessed for hazards, and the least hazardous option is used.

    - If needed, additives are chosen that stay in the product and do not migrate into living spaces or the environment.
  - End of life:
    - Additional hazardous substances are not required for processing at end of life.
    - Hazardous substances are not produced at the end of life (e.g. combustion by-products).
    - Legacy hazardous substances are not perpetuated in the supply chain as part of recycling processes.

- Transparency in terms of content and emissions exists at every step of the supply chain.
  - Third-party verified Health Product Declarations with all contents characterised, screened, and identified to 100 ppm are available for all products used in the manufacturing of the product.
  - Supply chain material flows for chemical inputs are identified.
  - Emissions data is publicly reported for all stages of chemical and product manufacture, and hazardous emissions are eliminated.

- Full hazard assessments are available
  - Full chemical hazard assessments are available on all chemicals used in a product and used to make the product.
  - Alternatives to chemicals of concern are fully disclosed, fully assessed alternatives of low concern.

Sustainable plastics are managed within a sustainable materials management system. They:

Have a commercial afterlife:

- Products are designed for durability, reclamation, reuse, and recycling
  - The product can be reclaimed and reused if removed before the end of its useful life.
  - The material is recyclable at the end of life into products with equal or greater value than the original product.

- Content transparency exists to support reuse and recycling
  - Products have public content transparency to aid in understanding of product content at this stage and potential impacts on recycling. Third-party verified Health Product Declarations with all contents characterised, screened, and identified to 100 ppm are available.

- Infrastructure exists to support reclamation, reuse, and recycling
  - Suitable reclamation and recycling infrastructure exists.

    - Partnerships and initiatives are in place to expand and improve reclamation and recycling infrastructure as part of the product development process.
    - Reclamation and recycling of materials when a building is constructed, renovated, or demolished is all part of an extended manufacturer responsibility program.
- Materials are able to undergo multiple cycles of recycling

Generate no waste

- Manufacturing waste is eliminated at every step of the production process.
- Scrap from installation is eliminated or recycled.

Use rapidly renewable resources or waste-derived materials

- Use rapidly renewable resources that don't compete with "higher" uses.
    - Biobased feedstocks are used when they don't compete with "higher" uses (e.g. food production) and when they have lower impacts than virgin materials.
- Use waste-derived materials without hazardous content.
    - Waste feedstocks are used and are from known sources and tested for common hazardous content to avoid introducing hazardous content into new products.

4.1. Application of Criteria to Case Study

No one plastic insulation product will currently meet all of the criteria outlined above. Furthermore, comparing products using these criteria is going to highlight differences, but also trade-offs between different product types. One way to use these criteria is demonstrated in Table 4.2. below. The products are compared side-by-side not only to compare impacts between the product types, but also to identify opportunities for mitigation and promote avoidance of shifting impacts to another life cycle stage.

Table 4.1. Comparison of EPS, XPS, Polyiso, and SPF insulation. Impacts and opportunities for mitigation

	Polystyrene		Polyurethane/Polyisocyanurate	
Criterion	**EPS**	**XPS**	**Polyiso**	**SPF**
Sustainable plastics enhance human and environmental health and safety across the entire product life cycle. They are:				
Inherently low hazard: Base polymer and source materials	**Impacts:** Two SIN List chemicals are inherent to polystyrene resin manufacture. Potential process chemical on SIN List but alternative available. Recycled EPS/XPS contains SVHC and POP chemical, HBCD. **Opportunities for mitigation:** Use certified recycled polystyrene from known sources without chemicals of concern instead of virgin polymer. Consider alternative plastic types with lower inherent hazards.		**Impacts:** Several SVHC and SIN List chemicals are inherent to polyurethane/polyisocyanurate manufacture. MDI monomer is a respiratory sensitiser. **Opportunities for mitigation:** Identify polyols with inherently safe inputs. Support green chemistry innovation for isocyanate-free polyurethane where alternatives are assessed and found to have lower inherent hazards. Consider alternative plastic types with lower inherent hazards. Consider alternative plastic types that are more readily recyclable to reduce use of virgin polymers.	
Inherently low hazard: Product manufacturing including Additives/Additive Life Cycle	**Impacts:** Flame retardants are halogenated and may be the SVHC and POP chemical HBCD (mostly phased out of new products). SIN List monomer may be a residual. **Opportunities for mitigation:** Adjust building codes to remove the necessity for flame retardants while maintaining fire safety (as in Scandinavia). Use fully disclosed, fully assessed alternatives of low concern. Support chemical restrictions and regulations using class-based approach.	**Impacts:** Flame retardants are halogenated and may be the SVHC and POP chemical HBCD (mostly phased out of new products). SIN List monomer may be a residual. Halogenated blowing agents are ODS and/or high GWP or use chemicals that are ODS and/or high GWP in their manufacture. **Opportunities for mitigation:** Adjust building codes to remove the necessity for flame retardants while maintaining fire safety (as in Scandinavia). Use fully disclosed, fully assessed alternatives of low concern. Support chemical restrictions and regulations using class-based approach. Consider novel additives of low inherent hazard or manufacturing processes to	**Impacts:** Flame retardants are typically halogenated and on SIN List. Potential SIN List blowing agent. Respiratory sensitiser isocyanates are key to chemistry. **Opportunities for mitigation:** Adjust building codes to remove the necessity for flame retardants while maintaining fire safety (as in Scandinavia). Use fully disclosed, fully assessed alternatives of low concern. Support chemical restrictions and regulations using class-based approach.	**Impacts:** Flame retardants are typically halogenated and on SIN List. SIN List catalyst. Respiratory sensitiser isocyanates are key to chemistry. Halogenated blowing agents are ODS and/or high GWP or use chemicals that are ODS and/or high GWP in their manufacture. **Opportunities for mitigation:** Adjust building codes to remove the necessity for flame retardants while maintaining fire safety (as in Scandinavia). Use fully disclosed, fully assessed alternatives of low concern. Support chemical restrictions and regulations using class-based approach. Consider novel additives of low inherent hazard or manufacturing processes to

		improve insulative performance while using non-halogenated blowing agents.		improve insulative performance while using non-halogenated blowing agents.
Inherently low hazard: During installation and use	**Impacts:** Flame retardants are halogenated and may be the SVHC and POP chemical HBCD (mostly phased out of new products). SIN List monomer may be a residual. **Opportunities for mitigation:** Adjust building codes to remove the necessity for flame retardants while maintaining fire safety (as in Scandinavia). Prefer additives that do not migrate from the product. Use fully disclosed, fully assessed alternatives of low concern. Support chemical restrictions and regulations using class-based approach.	**Impacts:** Flame retardants are halogenated and may be the SVHC and POP chemical HBCD (mostly phased out of new products). Many halogenated blowing agents are ODS and/or high GWP. **Opportunities for mitigation:** Adjust building codes to remove the necessity for flame retardants while maintaining fire safety (as in Scandinavia). Prefer additives that do not migrate from the product. Use fully disclosed, fully assessed alternatives of low concern. Support chemical restrictions and regulations using class-based approach.	**Impacts:** Flame retardants are typically halogenated and on SIN List. Potential SIN List blowing agent (uncommon). **Opportunities for mitigation:** Adjust building codes to remove the necessity for flame retardants while maintaining fire safety (as in Scandinavia). Prefer additives that do not migrate from the product. Use fully disclosed, fully assessed alternatives of low concern. Support chemical restrictions and regulations using class-based approach.	**Impacts:** Flame retardants are typically halogenated and on SIN List. SIN List catalyst. Respiratory sensitiser isocyanates are key to chemistry - particular impacts during and following installation. Additional SIN List chemical emissions. Final foam impacted by installation conditions. Many halogenated blowing agents are ODS and/or high GWP. **Opportunities for mitigation:** Adjust building codes to remove the necessity for flame retardants while maintaining fire safety (as in Scandinavia). Prefer additives that do not migrate from the product. Use fully disclosed, fully assessed alternatives of low concern. Support chemical restrictions and regulations using class-based approach. Consider where in the life cycle chemical reactions take place and avoid designing products that react on site where there is less control.
Inherently low hazard: End of life	**Impacts:** Landfill is currently the most common end of life for plastic insulation materials. Some regions may incinerate plastic insulation. Both can lead to the release of hazardous substances. Recycling can be energy- and material-intensive and can release hazardous substances present in the product or used in the recycling process. **Opportunities for mitigation:** Extended producer responsibility programs. Engage with recyclers. Support recycling infrastructure development and reuse innovations. Avoid use or production of hazardous substances during end of life processing.			
Transparent in terms of content and emissions	**Current state:** Disclosure of product content is occurring for some plastic insulation. The quality and completeness of this disclosure is inconsistent.			

at every step of the supply chain	**Opportunities for improvement:** Strive to generate a third-party verified Health Product Declarations with all contents characterised, screened, and identified to 100 ppm. Implement data collection for supply chain material flows and manufacturing emissions to the environment.		
Fully assessed for hazards	**Current state:** Few of the chemicals used in plastic insulation are fully assessed for hazards. **Opportunities for improvement:** Strive to generate full chemical hazard assessments on all chemicals used in an insulation product.		
Sustainable plastics are managed within a sustainable materials management system. They:			
Have a commercial afterlife	**Impacts:** Currently polystyrene insulation is most often landfilled. Legacy hazardous substances may make recycling more difficult or reduce the value of recycled material. **Opportunities for mitigation:** Extended producer responsibility programs. Engage with recyclers to develop or expand infrastructure. Consider infrastructure for reuse - boards may be reclaimed and reused. Use inherently low hazard chemicals in products, so they are more valuable at end of life. Transparency and labelling of products to identify those without legacy chemicals of concern for reuse or recycling.	**Impacts:** Currently polyiso insulation is most often landfilled. Legacy hazardous substances may make recycling more difficult or reduce the value of recycled material. The thermoset nature limits recycling options. **Opportunities for mitigation:** Extended producer responsibility programs. Engage with recyclers to develop or expand infrastructure. Consider infrastructure for reuse - boards may be reclaimed and reused. Use inherently low hazard chemicals in products, so they are more valuable at end of life. Transparency and labelling of products to identify those without legacy chemicals of concern for reuse or recycling.	**Impacts:** Currently SPF insulation is most often landfilled. Legacy hazardous substances may make recycling more difficult or reduce the value of recycled material. The thermoset nature limits recycling options. Reuse unlikely. **Opportunities for mitigation:** Extended producer responsibility programs. Engage with recyclers to develop or expand infrastructure. Use inherently low hazard chemicals in products, so they are more valuable at end of life. Transparency and labelling of products to identify those without legacy chemicals of concern for recycling.
Generate no waste	**Impacts:** Waste occurs during manufacturing, installation, and end of life. **Opportunities for mitigation:** Strive towards zero waste (including emissions) at manufacturing sites. Educate installers on ways to reduce and recycle scrap during installation. Recover and reuse board materials that are still functional at end of life. Generate reuse and recycling infrastructure and demand for reclaimed or recycled products.		**Impacts:** Waste occurs during manufacturing, installation, and end of life. Spray foam may adhere to and make other materials harder to recover. **Opportunities for mitigation:** Strive towards zero waste at manufacturing sites. Educate installers on ways to reduce and recycle scrap during installation. Generate recycling infrastructure and demand for recycled materials.
Use rapidly renewable resources or waste derived materials	**Impacts:** Use of recycled EPS or XPS in new insulation may reintroduce legacy hazards (e.g. HBCD). **Opportunities for mitigation:** Use recycled PS from known sources without chemicals of concern instead of virgin polymer.	**Impacts:** Recycled inputs for facing materials only. **Opportunities for mitigation:** Identify polyols with inputs from rapidly renewable resources that do not compete with higher uses. Consider alternative plastic types that are more readily	**Impacts:** Some use of biobased and recycled content in polyols. **Opportunities for mitigation:** Identify polyols with inputs from rapidly renewable resources that do not compete with higher uses and/or recycled content polyols that do

	Consider alternative plastic types that are more readily recyclable or have rapidly renewable inputs.	recyclable.	not contain chemicals of concern. Consider alternative plastic types that are more readily recyclable.

5. Conclusion

The sustainable plastic goals derived at the beginning of this case study informed the generation of key criteria that can be used by product design teams and procurement specialists to benchmark their current practices and identify opportunities for improvement. These opportunities include consideration of different materials, different manufacturing processes, different product designs, number and type of data gaps, and range of policy instruments that could reduce product impacts throughout the life cycle. While the criteria were developed with plastic insulation in mind, they are relevant for any durable plastic product.

As stated above, the sustainable plastic goals are lofty. Current products are unlikely to meet all of the criteria. While they may not be immediately achievable, the criteria provide a pathway toward truly sustainable plastic products. This case study focuses on comparing plastic insulation products; however, additional insulation materials such as fiberglass, mineral wool, cork, cellulose, etc. should be considered and compared from a sustainability perspective. In product design, innovation may require the consideration of different materials types and/or business models for products versus making incremental improvements in chemistry for a particular type of product. With any alternatives, evaluation of impacts at all stages of the product life cycle is important to make an informed decision. Products should be envisioned and designed within sustainable material systems.

For any product design or policy development, teams should decide early on based on their group's values which sustainability goals and criteria are most important to focus on and make decisions based on an understanding of the connection to other sustainability goals and the potential trade-offs. In addition to the comparison table above, various tools are available to help project teams make decisions in the face of multivariable data such as the criteria outlined in this case study (DM, 2010; OECD, 2018b). The sustainable plastic goals can be used in an iterative way, filling data gaps as needed to discern between options and to make informed decisions.

Annex A. Product Composition

A Common Product profile is a type of data record generated by Healthy Building Network and consists of a list of substances that are most commonly present in a product type as delivered to building sites. They are based on numerous sources including specific product literature, transparency documents, trade association data, industry standards, and patents. The profiles are not specific to any manufacturer. Although Common Products and the example formulations cited below are specific to product compositions available in North America, for the report above potential regional variations are discussed that may exist outside of this region. This same product information and original source documentation is also available in the Common Products section of the Pharos database (Healthy Building Network, no date c). Common Product research methodology is described in detail at https://pharosproject.net/common-products/methodology.

XPS Insulation (Extruded Polystyrene) Common Product*

Chemical	CASRN	% Weight Product	Function
Polystyrene	9003-53-6	88.3%	Base Resin
HFC-134A	811-97-2	6.2%	Blowing Agent
Methyl Formate	107-31-3	2.2%	Blowing Agent
Butadiene styrene brominated copolymer	1195978-93-8	1.7%	Flame Retardant
Pentane	109-66-0	0.9%	Blowing Agent
Talc	14807-96-6	0.3%	Nucleating Agent
Pentaerythritol tetrakis(3-(3,5-di-tert-butyl-4-hydroxyphenyl)propionate)	6683-19-8	0.2%	Stabiliser
Epichlorohydrin, O-cresol, Formaldehyde Polymer	29690-82-2	0.1%	Stabiliser
Calcium Stearate	1592-23-0	0.09%	Lubricant
3,9-Bis(2,4-di-tert-butylphenoxy)-2,4,8,10-tetraoxa-3,9-diphosphaspiro(5.5)undecane	26741-53-7	0.02%	Stabiliser

* *For a full list of sources used to generate this Common Product see XPS Insulation (extruded polystyrene) (2019) Pharos. Available at: https://pharosproject.net/common-products/2078867 (Accessed: 21 January 2021).*

EPS Insulation (Expanded PolyStyrene) Common Product*

Chemical	CASRN	% Weight Product	Function
Polystyrene	9003-53-6	96.0%	Base Resin
Butadiene styrene brominated copolymer	1195978-93-8	1.0%	Flame Retardant
Pentane	109-66-0	0.9%	Blowing Agent
Cyclopentane	287-92-3	0.6%	Blowing Agent
Isopentane	78-78-4	0.6%	Blowing Agent
Tristearin	555-43-1	0.5%	Antistatic/Lubricant
Polyethylene	9002-88-4	0.3%	Nucleating Agent
Zinc Stearate	557-05-1	0.1%	Antistatic/Lubricant
Styrene	100-42-5	0.1%	Residual Monomer

**For a full list of sources used to generate this Common Product see EPS Insulation (expanded polystyrene) (2019) Pharos. Available at: https://pharosproject.net/common-products/2079007 (Accessed: 21 January 2021).*

Polyisocyanurate Wall Insulation Board Common Product*

Chemical	CASRN	% Weight Product	Function
Polyisocyanurate Foam	9063-78-9	76.1%	Insulating Foam
Tris(2-chloroisopropyl) phosphate	13674-84-5	5.8%	Flame Retardant
Pentane	109-66-0	5.3%	Blowing Agent
Fiberglass	65997-17-3	2.6%	Core Fire Resistance
Potassium 2-ethylhexanoate	3164-85-0	1.3%	Catalyst
1,2-Propanediol, polymer with 2-ethyloxirane and oxirane, potassium salt	134737-27-2	0.7%	Surfactant
Potassium acetate	127-08-2	0.2%	Catalyst
1,2-Ethanediamine, N1-(2-(dimethylamino)ethyl)-N1,N2,N2-trimethyl-	3030-47-5	0.1%	Catalyst
Polyethylene	9002-88-4	4.4%	Adhesive
Aluminium	7429-90-5	1.7%	Vapour Barrier
Cellulose, microcrystalline	9004-34-6	1.5%	Kraft Paper
Calcium carbonate	471-34-1	0.1%	Filler in Kraft Paper

Titanium dioxide	13463-67-7	0.03%	Filler in Kraft Paper
Starch	9005-25-8	0.01%	Sizing Agent in Kraft Paper
Aluminium sulphate anhydrous	10043-01-3	0.01%	Sizing Agent in Kraft Paper

** For a full list of sources used to generate this Common Product see Polyisocyanurate Wall Insulation Board (2016) Pharos. Available at: https://pharosproject.net/common-products/2085579 (Accessed: 21 January 2021).*

Spray Foam Insulation Common Product*

Chemical	CASRN	% Weight Product	Function
Polymethylene polyphenyl isocyanate	9016-87-9	30.9%	Prepolymer - A Side
4,4'-Diphenylmethane diisocyanate	101-68-8	20.1%	Monomer - A Side
1,4-Benzenedicarboxylic acid, 1,4-dimethyl ester, manuf. of, by-products from, polymers with diethylene glycol	70749-97-2	22.5%	Polyol - B Side
1,3-Benzenediamine, ar-methyl-, polymer with oxirane	63641-64-5	7.2%	Polyol - B Side
Formaldehyde, polymer with methyloxirane, oxirane and phenol	25134-86-5	5.5%	Polyol - B Side
Tris(2-chloroisopropyl) phosphate	13674-84-5	5.2%	Flame Retardant - B Side
HFC 245fa	460-73-1	4.7%	Blowing Agent - B Side
Water	7732-18-5	1.1%	Blowing Agent - B Side
N,N-Dimethylcyclohexylamine	98-94-2	0.6%	Catalyst - B Side
Silicone L-5310	87244-72-2	0.5%	Surfactant - B Side
1,3-Propanediamine, N1,N1-bis(3-(dimethylamino)propyl)-N3,N3-dimethyl-	33329-35-0	0.4%	Catalyst - B Side
1,2-Ethanediamine, N1-(2-(dimethylamino)ethyl)-N1,N2,N2-trimethyl-	3030-47-5	0.4%	Catalyst - B Side
Dibutyltin dilaurate	77-58-7	0.2%	Catalyst - B Side
Diethylene Glycol	111-46-6	0.7%	Polyol Residual Catalyst/Solvent - B Side
Formaldehyde	50-00-0	0.01%	Polyol Residual - B Side

** For a full list of sources used to generate this Common Product see Spray Foam Insulation (2015) Pharos. Available at: https://pharosproject.net/common-products/2079008 (Accessed: 21 January 2021).*

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