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Adhesives & sealants: sustainability in the construction sector

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1 Introduction

The sustainability of products in the construction sector is deservedly receiving high attention in the European Union (EU) in recent years. The importance of this subject is justified both by the absolute scale of the construction sector as well as its share in the materials used and produced in the EU and the share of greenhouse gas emissions it represents[1], [2]. Consequently, recent legislative initiatives focused on sustainability, such as the EU Green Deal, cover the construction sector explicitly and with specific provisions.

This attention concerns all levels, from entire buildings to individual construction elements and down to the materials used for their production and installation. As such, adhesives and sealants for the construction sector and their impact on the sustainability of the built environment are of high interest, as well.

This report aims to provide an overview of key aspects of sustainability as related to adhesives and sealants in the construction sector, considering both the current state and the future.

This introductory chapter will provide a brief overview of the scale of the construction sector, certain aspects that are particular to this industry – differentiating it, e.g., from the consumer goods sectors – and describe current and recent legislative initiatives that affect construction products and the construction sector in the EU. Following chapters will describe two important sides of sustainability in the construction sector: **energy efficiency** and **material efficiency**. Additionally, more detailed information will be provided on adhesives and sealants in recycling processes and on methods to quantify the environmental performance of adhesives and sealants.

1.1 The scale of the construction sector

On a global level, approximately 40% of all materials are used in the construction sector[3]. As such, this sector has very measurable impacts globally, both in economical as well as in environmental terms.

According to data used by the European Commission, the full life cycle of buildings[1] in the EU accounts for

- ca. 50% of the total energy use
- ca. 40% of the total greenhouse gas emissions
- ca. 50% of the raw material extraction
- ca. 30% of all water use[2]

In addition, the construction sector is also a notable contributor to the volume of end-of-life materials ('waste'), constituting 25-30% of the total waste by weight in the EU[3].

With substantial contributions to the overall energy and material footprint of the European economy, as well as considering the importance of buildings in the daily life of citizens, a specific and detailed consideration of sustainability in the construction sector is clearly warranted.

1.2 Unique features of the construction sector

The construction sector exhibits unique features that should be taken into account when discussing sustainability and effective improvement approaches.

[1] This includes the extraction of raw materials, manufacture of construction products, their transport, the actual construction activities, the use phase, and end-of-life (demolition and waste treatment).

The mass (weight) of materials utilised in construction is very high, both in its totality as well as per unit of construction product. This is particularly apparent when compared with, for example, consumer goods or electronics. The high masses have implications on the sourcing and transport of raw materials, finished products and demolition waste. At the same time, construction products are typically also large in size, encouraging on-site renovation and repair as well as allowing for manual selective dismantling or replacement. This can be illustrated, for example, by a door, which may be repaired and repainted when damaged or worn rather than immediately replaced. When replacement does become necessary, the removal of the door and its frame can easily be performed manually, without special technology required. This contrasts with markets for highly complex, small items (such as electronics) or markets with very high numbers of smaller, lower value items (such as textiles or low-cost consumer goods which are often not repaired).

Additionally, the lifetimes of products in the construction sector are exceptionally long, measured in decades as opposed to weeks, months, or years as in other sectors.[2] This opens up opportunities not available to other sectors, such as the sequestration of carbon, but at the same time introduces challenges in waste management which are not found in this form in other markets. In particular, the long lifetimes imply that a construction product installed today will (have to) be treated by the waste treatment infrastructure of 50-100 years in the future, whose properties are not readily predicted in detail. These aspects will be discussed in more detail below.

In sum, while the same universal principles of sustainability apply to the construction sector, it is important to consider that, due to above described features, effective solutions to improve sustainability may differ substantially from other sectors.

1.3 Two key sides of sustainability in the construction sector

Considering the long lifespan of buildings, it becomes clear that the (very long) use phase can have an outsized impact on the overall environmental footprint and sustainability of construction products and entire buildings. Consequently, it is not surprising that in the EU, existing buildings are responsible for 36% of greenhouse gas emissions[1]. These greenhouse gas emissions generated during the use phase are related mainly to the energy usage of a building. Energies used for heating (and cooling) buildings dominate these emissions. A reduction in use phase emissions from buildings is therefore primarily achieved by increasing the (thermal) *energy efficiency*[3] of the building. With the reduction of greenhouse gas emissions being a main societal and political aim, the **energy efficiency** of construction products and buildings becomes an important lever.

When considering the whole life cycle of a building from construction to demolition, its overall emissions and environmental footprint include, however, not only the use phase but also the footprint and the 'embodied' greenhouse gas emissions of the installed materials. These emissions are typically referred to as the **'embodied carbon'** of the building and cannot be reduced by use phase **energy efficiency** measures; they must be addressed through **material efficiency.**

It is important to point out that, with increasing **energy efficiency** and a transition to renewable energy sources, emissions from the use phase of buildings will drop and eventually reach (net) zero, in line with the ambitions of the EU Climate Law.[4] Thus, with every improvement in **energy efficiency**,

[2] By convention, the lifetime of a building is 50-80 years, but in practice, buildings remain in use for substantially longer.

[3] Energy efficiency in this report relates only to the building's use phase. Energies used for the production of construction products are covered under materials, as embodied carbon.

[4] Even with fully sustainable energies, energy efficiency remains important. This relates not only to costs for residents but also to the availability of renewable energies. An 'oversupply' of renewables is not likely in the near and medium-term future, meaning that more efficiency means that more buildings can be converted to sustainable energies within an existing energy budget than without efficiency.

material efficiency will become more important to achieve further total life cycle improvements in a building's environmental footprint.

In the following main chapters, this report will explore how these two key sides of energy efficiency and material efficiency can improve sustainability in the construction sector and highlight what impacts and benefits adhesives and sealants can impart.

1.4 The European Green Deal

The EU Green Deal[4] is an ambitious legislative sustainability package that directly targets also the construction sector ('the built environment'). In addition, the EU Green Deal covers aspects such as greenhouse gas emissions, climate, energy, sustainable products and the circular economy (Figure 1), which cut across most industry sectors.[5] In the following subsections, key elements of the EU Green Deal (Figure 2) will be described.

Figure 1: Overview of the key aims of the EU Green Deal (Source: EU Commission).

[5] It should be noted that aside from the EU Green Deal, other regulation in the EU will also affect the construction sector, for example REACH and CLP regulations. In addition to the EU-wide measures, EU member states themselves are also active on many of the same topics.

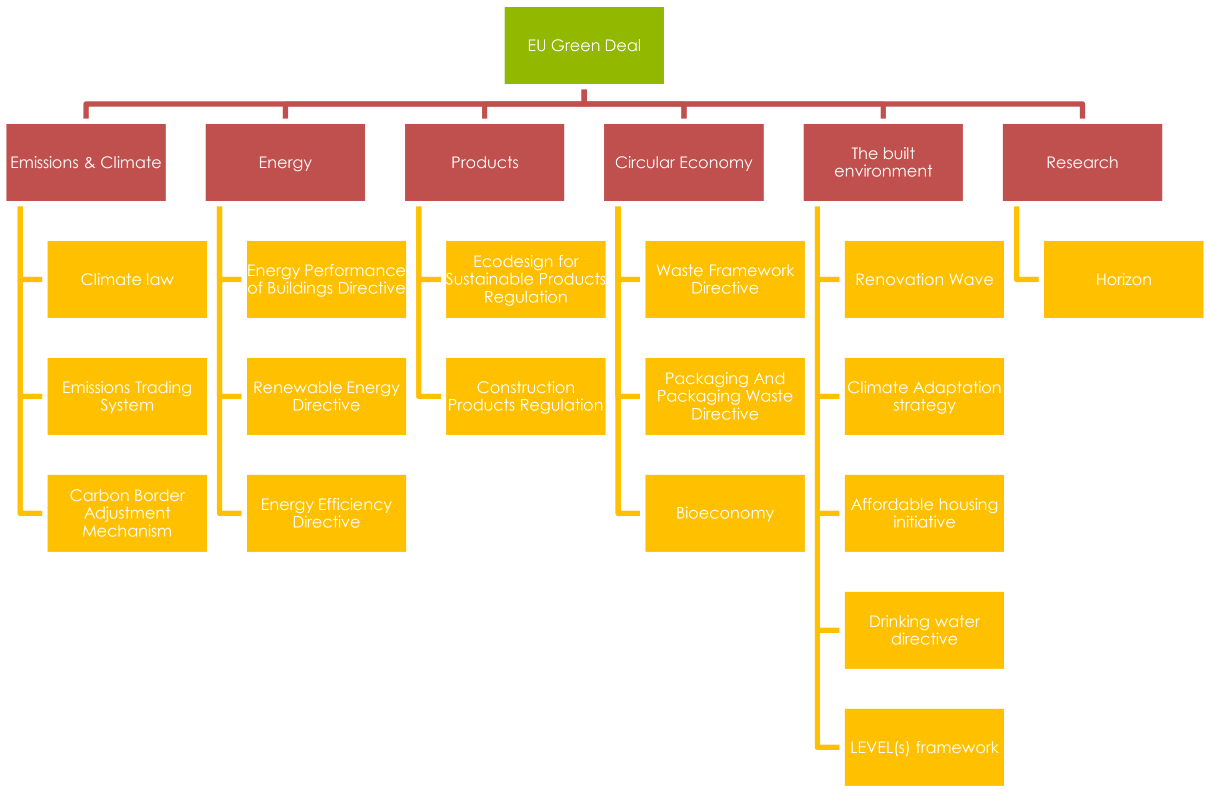

Figure 2: Initiatives and legislation related to the EU Green Deal (excerpt).

2 EU Climate Law

The EU Climate Law[5] provides the legal basis for Europe becoming net-zero[6] on greenhouse gas emissions by 2050. An interim reduction target of 55%, compared to the levels in 1990, is set for 2030. These targets include all sectors of the economy and can only be met if a reduction of buildings' emissions, which in the EU are responsible for 36% of all greenhouse gas emissions[1], can be achieved.

3 EU Sustainable Products Initiative

The EU current proposal for an Ecodesign for Sustainable Products Regulation [6] intends to replace the EU Eco-Design Directive, with a focus on making a wide range of products in the EU more sustainable. This constitutes a continuation of the **energy efficiency** approach of the Eco-Design Directive, which covers energy-related products and will introduce additional aspects of **circularity**, such as durability, reusability, repairability and recyclability as well as use of recycled materials. Detailed provisions will be part of delegated acts under the regulation.

4 EU Construction Products Regulation

The EU Construction Products Regulation[7] lays down harmonised rules for the marketing of construction products in the EU. In its current form, its requirements on sustainability are relatively generic. A review of the Construction Products Regulation is part of the EU Green Deal agenda and is likely to focus on sustainability aspects, such as mandatory recycled content quotas, product safety and requirements to declare the Product Environmental Footprint.

[6] Meaning total emissions minus credits for the capture / storage of atmospheric carbon dioxide, e.g., by forest cover increases or by technical measures.

5 EU Renovation Wave

The EU Renovation Wave[8] is an initiative focused on the **energy renovation** of buildings in the EU. Its target is a 3% annual energy renovation rate, up from 1% at time of writing.

While **energy efficiency** is a key target for the EU Renovation Wave, social considerations are also explicitly mentioned. These include ensuring the occupational health and safety of workers in construction, increasing the presence and role of women in the construction sector, decreasing the risk of energy poverty among EU citizens, and improving climate resilience standards for buildings, thereby protecting inhabitants' health.

The EU Renovation Wave, while focused on **energy efficiency**, also considers **material efficiency** and **circularity** as ways of reducing the whole life cycle carbon emissions of buildings.

6 EU Energy Performance of Buildings Directive

The EU Energy Performance of Buildings Directive[9] is a proposal for the concrete implementation of goals of the EU Renovation Wave. In line with the aims of the EU Climate Law, its vision is a (net) zero emission building stock by 2050. The achievement of this goal is clearly tied to renovation as almost 75% of the current building stock in the EU is considered to be inefficient according to current building standards and 85-95% of these buildings are expected to still be standing in 2050[9].

The need for a specific directive on buildings is seen because existing and planned measures on carbon pricing (EU Emissions Trading System, EU Carbon Border Adjustment Mechanism) are not considered to provide sufficient incentive to drive energy renovation at a rate required to meet the targets of the EU Climate Law.

The focus of the directive proposal is first on the worst performing non-residential buildings, an approach taken also due to the relative availability of capital to commercial versus private owners of buildings.

The EU Energy Performance of Buildings Directive proposal also provides a legal basis for national bans of boilers that rely on fossil fuels.

It is worth pointing out that the proposal, while focused on **energy efficiency**, also includes a consideration of *material efficiency* (Recital 8), of **circularity** and of *embodied carbon* in construction products (Recital 9).

7 EU Emissions Trading System

The current EU Emissions Trading System[10] covers the production of certain construction materials, namely iron, steel, cement, glass and ceramics. The Emissions Trading System already also covers directly or indirectly around 30% of buildings' emissions from heating, caused by the system's coverage of district heating and electricity generation (used in part for electrical heating).

The EU Commission has proposed to establish a separate emissions trading system for road transport and heating of buildings by 2025[11] as an additional incentive for the energy renovation of buildings. As there are a large number of small emitters in the building sector (individual houses), the point of regulation is to be established not with the emitters, but further upstream in the supply chain, that is, on the level of fuel or energy supply.

8 EU Carbon Border Adjustment Mechanism

The EU is planning to create a new levy on imported goods, to prevent 'carbon leakage' to countries with less stringent climate ambitions or lower carbon taxation. This approach is referred to as the EU Carbon Border Adjustment Mechanism[12].

The current proposal includes certain construction related materials, i.e., cement, iron, steel and aluminium. The envisaged levy would be applied to imported raw materials, not to imported finished products. If implemented as proposed, in addition to changing the relative prices of imported vs. domestic cement, iron, steel and aluminium, the importation of wood, glass and plastics may become more cost competitive compared to that of the former materials.

Higher prices may also improve the profitability of and demand for recycling and reuse of materials. An overall increase of construction material prices could furthermore incentivise renovation over full rebuilding, where such a choice exists.

9 EU Taxonomy for Sustainable Activities

The EU Taxonomy for Sustainable Activities[13] aims to incentivise capital flows towards improvements in sustainability. It does so by helping investors navigate the arguably complex technical landscape related to the transition to a low carbon and resource efficient economy.

The taxonomy covers the construction sector and defines what constitutes a 'Substantial Contribution' to sustainability in construction. A substantial contribution is possible for both renovation and new construction and predicated on meeting certain energy performance criteria. For large building projects, the taxonomy considers the 'Life cycle footprint', addressing also **embodied carbon** in addition to the use phase energy footprint.

Additionally, construction principles are expected to consider **circularity** and enable disassembly. Consistently, the 'Do-no-significant-harm' checks require reuse, recycling or material recovery of construction and demolition wastes, covering at least 70% by weight of the total waste.

10 EU Bioeconomy Strategy

The EU Bioeconomy Strategy[14] considers use of wood and other forestry products as sustainable alternatives to existing raw materials, including those in the chemical sector. This approach matches the **renewable carbon** concept, discussed further below.

Furthermore, the strategy actively supports an increased use of wood products in construction, on the basis that 1 ton of wood instead of 1 ton of concrete is understood to yield an average reduction of 2.1 tons of (embodied) CO_2 emissions[14]. In addition, the option of carbon sequestration[7] by storing wood (from sustainable forestry) in the long-lived built environment is considered.

11 EU Waste Framework Directive

The EU Waste Framework Directive[15] contains important provisions related to waste in general and also to the construction sector in particular.

Fundamentally, it defines and enforces a waste hierarchy (as will be discussed below), and thereby also promotes selective demolition and waste sorting.

[7] Note should, however, be taken of the IPCC's carbon accounting methodology and the timeframes considered to represent permanent sequestration of carbon.

The Waste Framework Directive also contains targets for the recovery and recycling of construction-related waste of 70% by 2020, which was overachieved in some countries already by 2016[16]. Future revisions of the directive, such as the one planned for 2023 as part of the EU Strategy for a Sustainable Built Environment, may update these quotas.

Finally, the directive defines **end-of-waste criteria**, that is, gives a definition of at what point a reprocessed waste material legally becomes a product again.[8] Currently, **end-of-waste criteria** are defined for iron, steel, aluminium, copper scrap and for glass cullet; criteria for other materials are still missing.

12 EU Levels Framework

The EU LEVEL(S) framework[17], [18] is a multidimensional building assessment framework supported by the European Commission and the EU Joint Research Centre (JRC). It considers four key dimensions, the first two of which align with **energy efficiency** and **material efficiency** as discussed in this report:

1. Greenhouse gas and air pollutant emissions along life
2. Resource efficient and circular material life cycles
3. Efficient use of water resources
4. Healthy and comfortable spaces

Its use is supported by recitals of the EU Renovation Wave and the EU Energy Performance of Buildings Directive.

13 EU Principles for Sustainable Raw Materials

The EU Principles for Sustainable Raw Materials[19] provide guidance on questions of sustainable materials extraction, but not on further processed or refined products. Secondary materials from construction and demolitions waste streams are also not part of their scope. The principles are therefore not discussed in this report.

14 Energy efficiency

In the EU, heating, cooling and domestic hot water account for around 80% of energy consumed in residential buildings[8]. Due to currently predominantly fossil energy sources, particularly for heating, this energy corresponds to a substantial part of the greenhouse gas emissions of a building. Consequently, thermal insulation and efficient heat sources are key levers for the **energy efficiency** of buildings.

Beyond sustainability contributions, improved insulation of buildings provides social co-benefits. Thermal insulation keeps inside temperatures within a narrower range, thereby protecting, in particular, vulnerable populations from cold and heat[20]. Many thermal insulation measures carry a co-benefit of noise insulation, providing quieter, more liveable indoor spaces[8]. Finally, insulation leads to heating cost savings for citizens, reducing their risk of being affected by energy poverty[8].

Adhesives and sealants can enable, improve and/or supplement a wide range of energy efficiency and energy saving measures in the construction sector. This section will describe key examples.

[8] At which point, product related regulation, including REACH, begins to apply.

14.1 External thermal insulation systems

Substantial savings of heating energy and greenhouse gas emissions (due to today's predominantly fossil heat sources) are possible through thermal insulation. The savings potential is estimated to be about ~80%[21] over a non-insulated building. As a co-benefit, additional savings for cooling energy can be obtained in case the building is also actively cooled in warm months. This co-benefit may increase in relevance as air conditioning is being installed more widely as a form of climate adaptation.

As part of the installation of external thermal insulation systems (Figure 3), adhesives increase the durability and performance of insulation panels[22]. Because adhesives allow for area bonding, high shear and peel resistance are realised, keeping panels reliably in place. By accommodating thermal deformation stresses, adhesive-based installation of foam insulation panels reduces the risk of damage (cracking) compared to mechanical anchor-based installation. In combination, a more consistent and reliable insulation is achieved.

Polyurethane (PU) foams provide insulating gap filling properties that augment the overall performance of external thermal insulation systems and buildings. PU foams allow, for example, for the compliant integration of windows and doors into the building envelope without thermal bridges (Figure 4); they can also fill gaps in external thermal insulation systems (Figure 5).

Figure 3: Installation of an external thermal insulation system with adhesives instead of mechanical anchors.

Figure 4: Use of polyurethane (PU) foam for insulating gap filling around window elements.


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Figure 5: Use of polyurethane foam to fill gaps in external thermal insulation systems.

14.2 Airtightness of building envelopes

Airtightness is crucially important to the overall thermal insulation performance of a building, as air leakage can represent up to 50% of the energy losses of a building[23], [24]. Additional benefits of airtightness can result from keeping insulation materials free of humidity and thereby allowing them to perform better.

Airtightness is achieved by using self-adhesive tapes (Figure 6), typically to bridge seams between insulation elements or membranes sheets, and by using different types of cartridge-applied sealants to provide air tightness around window elements (Figure 7) or to connect membranes to the building's structure.

Sealants and adhesive tapes are unique in providing airtightness to the building envelope. Construction elements such as windows cannot be produced or fit to tolerances that would provide an airtight fit on their own, and mechanical fastening of insulation panels or membranes typically creates additional air leaks (holes).

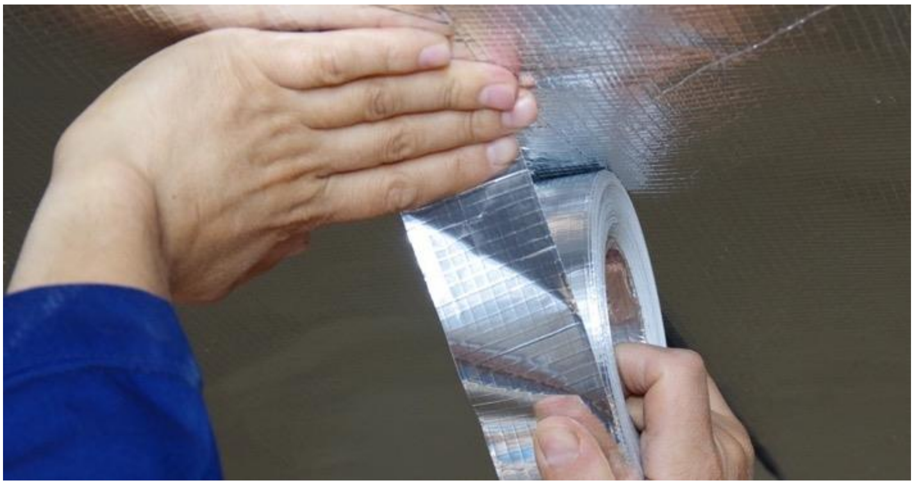
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Figure 6: Use of self-adhesive tape to provide airtightness along the seams between in-roof insulation panels.

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Figure 7: Use of silicone sealant to provide airtightness around a window frame.

14.3 Insulating windows and glazing elements

Modern architecture relies heavily on large glass areas, to provide ample lighting to indoor areas. Depending on their orientation, an additional benefit of direct solar heating is also obtained from large windows or glazing elements.

Sealants are key for the energy efficiency of multipaned glass windows (Figure 8) and glazing elements (Figure 9)[24]. Sealants retain the inert gas filling in-between panes, improving the insulation value; they also improve longevity by keeping humidity out from the intra-pane area.

While framed windows typically found in residential buildings are installed by a combination of mechanical fastening and PU foam, highly insulated glazing elements can also be directly bonded and sealed airtight to the building envelope (Figure 10), by using adhesives and sealants[25]. This modern, efficient architectural approach has paved the path away from concrete dominated facades of commercial and public buildings.

14.4 Transition to sustainable heating and domestic electrical energy

In addition to improvements in energy efficiency, adhesives and sealants are also key to the transition to decarbonised heat sources, supporting the replacement of the currently dominant types of heat sources that are based on combustion of fossil fuels.

For example, adhesives and sealants are key for the production of photovoltaic panels (Figure 11), which can provide sustainable electrical energy to drive heat pumps, both for heating and cooling as well as for hot water generation. Modern batteries, which allow storing surplus daytime electrical energy from photovoltaic systems for use during the night (Figure 13), are also made possible only with adhesives and sealants. Adhesives and sealants are, furthermore, used in the production of solar thermal hot water generation units (Figure 12), which can replace gas, oil, or electrically powered water heaters in many geographies.

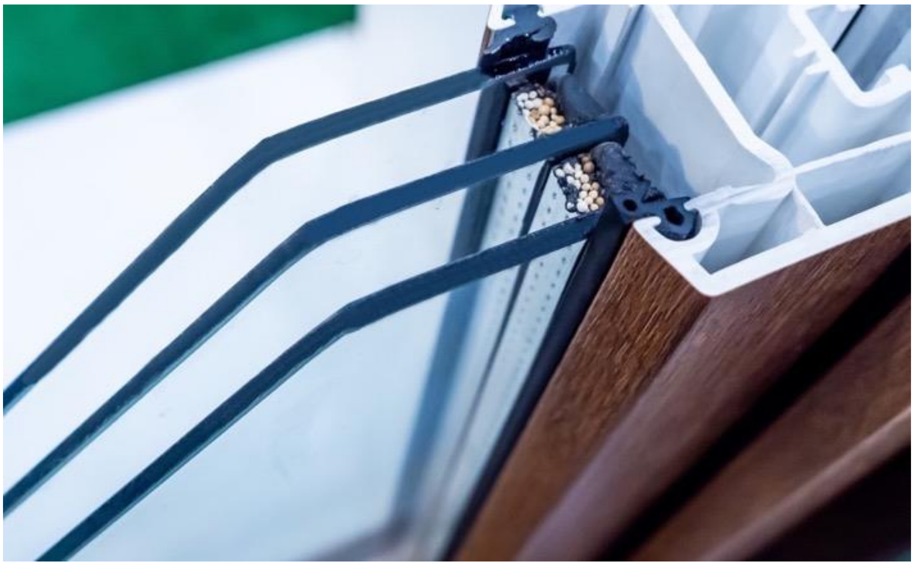

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Figure 8: Cross-section of a multipaned window, showing the sealant application.

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Figure 9: Closeup of the sealed edge of a multipaned glazing element.

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Figure 10: Typical outside view of a glass facade with directly bonded elements.

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Figure 11: Photovoltaic elements are a key to sustainable energy for heating, cooling, warm water and general electricity demand of a building.

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Figure 12: Solar thermal units can replace conventional warm water heaters.

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Figure 13: Storage batteries connected to photovoltaic systems can store surplus energy for night time use.

15 Material efficiency

Material efficiency is about maximising productive use of employed materials and minimising waste, which represents loss of material. **Material efficiency** is not only an economically attractive practice but also provides substantial ecological benefits.

Efficient use of materials supports the preservation of **depletable resources**, which is particularly relevant for inorganic and fossil-based materials for which natural reservoirs are not replenished (in distinction to, for example, biomass).

The reduction of waste avoids the associated footprint as well as possible further negative side effects of waste disposal.

Importantly, with rising energy efficiency, the **embodied carbon** footprint of buildings becomes more important. **In fact,** in modern, highly energy-efficient buildings, **embodied carbon** can be higher than the 50-year use-phase emissions[26].

Embodied carbon cannot be reduced by use phase energy efficiency measures; it must be addressed through material efficiency. Material-efficient construction with low footprint / low embedded carbon materials therefore becomes key for further overall reductions of a building's footprint.

A key tool in discussing **material efficiency** is the waste hierarchy, shown in Figure 14 (adapted to the construction sector). The waste hierarchy defines the most and the least preferable approaches to the use of materials from the angle of the waste that is created. As described above, waste can be understood as the inverse of **material efficiency.**

At the top of the hierarchy, i.e., most preferred, is the full avoidance or the reduction of material use already in the product design and manufacturing phases. Material that is not used in the first place, does not carry a footprint, and does not occur as waste at end-of-life. This means that material-efficient production is a key priority.

Next in preference are maintenance, repair, overhaul - in the case of the construction sector, often also referred to as renovation - which all extend the service life of building and therefore maximise the return on employed materials and delay the onset of end-of-life.

When the end-of-life of parts of the whole of a building is invariably reached, two options are clearly preferred over energy recovery or plain disposal. These are, in order of preference, reuse (of building components) and recycling (of materials). These two options can, in particular, be considered '**circular**' solutions that return end-of-life materials to another use.

When utilising the waste hierarchy, it is important to consider that while there is a clear hierarchy between the options it refers to, a wholistic analysis is important for optimum solutions. A wholistic approach avoids that a sole focus one step of the hierarchy, e.g., recycling, causes unwanted effects, e.g., on reduction[27].

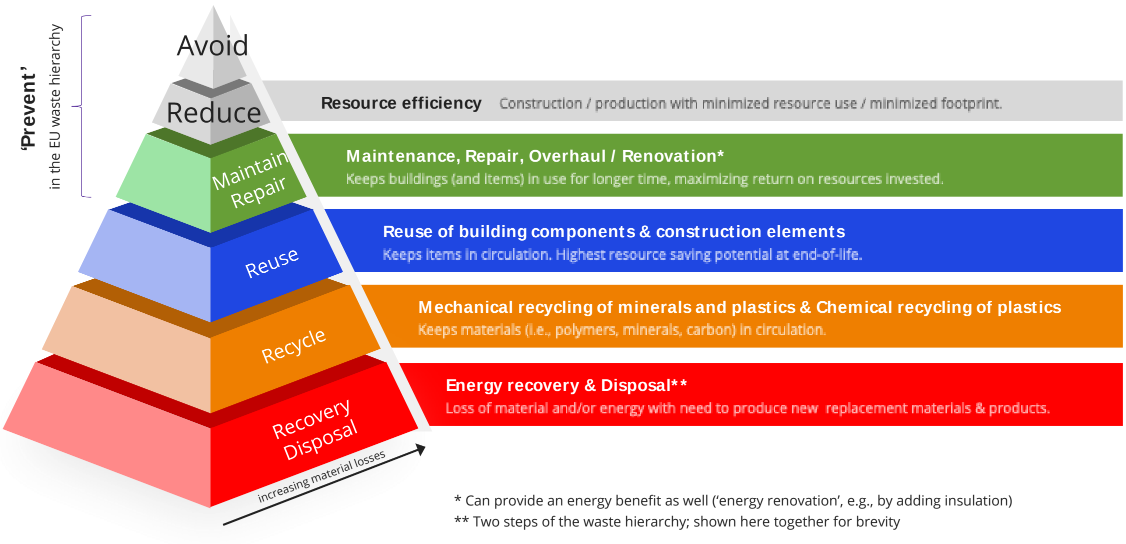

Figure 14: Visualisation of the waste hierarchy, adapted to the construction sector.

Strong **material efficiency** potentials exist in the construction section, allowing for footprint reductions. According to a study by the European Environment Agency[28], selected actions can provide a reduction of > 60% of the materials-related greenhouse gas emissions (**embedded carbon**) during the building's life cycle.

Key actions identified in an EU commissioned study[29] include the reduction of material use (lightweighting), reuse of construction elements and alternatives to cement and steel as construction materials. Notably, 'increase recycling rate' is not among the highest priority actions identified by this study. This can be understood when considering the already high recycling rates for many construction materials (e.g., construction steel, mineral materials) as will also be described further below.

The following sections will explore how adhesives and sealants can allow or enable preferable pathways of reduction, maintenance, repair, renovation, reuse and recycling of construction materials.

15.1 Reduction of material use and more sustainable materials

Adhesives and sealants can increase **material efficiency** by allowing for the reduction of material use. Additionally, they can also enable the use of lower **embedded carbon** construction materials, compared with conventional solutions.

In the example of glazing elements (Figure 9, Figure 10) for commercial and public building architecture, the metal profile width that is required for the installation of the glazing element can be minimised through high-performance sealants[25], affording a material use reduction. Adhesives can additionally substitute for steel reinforcements of the glazing elements themselves, enabling direct bonding of glass to frame.

Adhesives can enable the use of renewable, low carbon footprint construction materials, for example, wood. Engineered wood elements can replace steel beams (Figure 15) and concrete elements[30] in both residential and commercial construction. Notable savings in **embodied carbon** due to both wood's biobased origin as well as reduced fossil energy use during production can be obtained. In particular, 1 ton of wood instead of 1 ton of concrete used in construction is understood to yield an average reduction of 2.1 tons of CO_2 emissions[14]. Adhesives form a crucial component for engineered wood elements, ensuring quality, longevity and reliability.

Combinations of material use reduction and sustainable construction materials are also possible, for example in hollow core doors that contain a paper honeycomb inner construction in a wood frame[31], providing an overall materials weight saving.

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Figure 15: Example of an engineered wood construction.

15.2 Reduction of embedded carbon in adhesives and sealants themselves

The energy sector, metals and cement are on a path to 'decarbonisation' by replacing fossil-based energy sources and the use of carbon as a chemical reducing agent. 'Decarbonisation' is, however, not a useful concept for many other sectors as many materials contain carbon as part of their chemical makeup, e.g., wood, paper, plastics and most chemicals, including adhesives and sealants.

The concept of **renewable carbon** is therefore more useful for sectors such as adhesives and sealants: rather than aiming to replace or remove carbon (which is not possible), this approach focuses on ensuring the **circularity** of the carbon so as to prevent a net addition of carbon to the atmosphere. By preventing net greenhouse gas emissions, **renewable carbon** can reduce the **embodied carbon** footprint of adhesives and sealants. **Renewable carbon** can come from the biosphere, atmosphere or technosphere (recycling) – but not from the geosphere (mining, extraction)[32].

Biobased raw materials are already established in the production of adhesives and sealants. Raw materials from chemical recycling, including from construction materials, are becoming available for use in adhesives and sealants. For example, very active developments are underway to obtain styrene monomer and PU raw materials from waste insulation foams. As another example shows[33], the recycling of unused adhesives and sealants or their residues is another interesting opportunity.

Cementitious materials, also in use in certain construction adhesives, are a special case. In addition to the high energy demands for their production, CO_2 is released from a chemical reaction during the process of conversion of carbonate into clinker. Therefore, a full 'decarbonisation' of cement is not possible by moving to renewable energy.

The consequently high **embodied carbon** content of cement leads to a higher **embodied carbon** footprint of cementitious adhesives. New cement types[34], [35] and the use of recycled inorganic raw materials ('urban mining')[36] could offer pathways to reducing chemically emitted carbon and energies of production (and possibly transportation). Carbon capture technologies may be applied to mitigate chemically emitted carbon during cement production.

15.3 Maintenance, Repair and Renovation

Renovation is key for EU climate targets because most buildings will still be in use in 2050, when climate targets are to be reached[37]. Renovation also provides substantial energy and footprint savings over rebuilding: the added **embodied carbon** from renovation is typically less than 50% of the amount for a new building[37].

The benefits afforded by adhesives and sealants described in Section 14 are equally available during renovation as in new constructions.

In addition, during building maintenance and repair, adhesives and sealants can keep more material in use for longer periods of time. As part of maintenance activities, for example, façade sealants can extend building lifetime and prevent damages (Figure 16). Adhesives and sealants can prevent the replacement of entire building elements by allowing for repair, for example, window repair by replacing only broken glass while retaining the frame. Adhesives and sealants can also help the prevention of follow-on damages by mending damages quickly, for example, sealing of damaged rain gutters.

Aside from buildings themselves, adhesives and sealants are also key to the maintenance and repair of machinery. In the EU, about 20% of machinery is intended for use in construction[38], as are 15% of the total repair and installation of machinery and equipment efforts in the EU. Important applications include thread locking, retaining, gasketing, sealing, vehicle window repair and more (Figure 17).

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Figure 16: Maintenance of a glazed window front with a façade sealant.

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Figure 17: Maintenance and repair of machinery rely on adhesives and sealants.

15.4 Reuse of building elements

Reuse has a very high footprint savings potential[29] as it requires the least amount of reprocessing before the next life of the item and thus material. For example, reuse can substantially improve the footprint of steel elements[38]. Consequently, reuse is already in the scope of the EU Commission's thinking[38].

Reuse is today practiced for steel elements[39], [40], but timber and engineered wood are also a possibility[41]. Reuse of concrete elements appears to be also possible in principle but the lack of standardisation of element sizes and the relatively inhomogeneous use, which peaked in the 1980s, make this an economically more challenging market[41]. Recertification approaches exist for steel elements[42] to ensure safety and durability beyond initial use. Reuse of construction elements may introduce new design, debonding and cleaning requirements, including the removal of adhesive and sealant residues.

More standardised building design may increase the reuse potential. Such design may include an increased use of prefabricated building elements[3]. Aside from the reuse aspect, prefabrication is considered to carry opportunities in terms of improvements in quality control (e.g., more consistent insulation results), as well as additional social benefits, such as workplace safety, gender balance in the construction sector[37] and lower cost, more affordable housing[43]. Adhesives and sealants can support prefabrication, including automation, as can be seen from their widespread use in, for example, the automotive and electronics industries.

15.5 Recycling

As the lifetime of buildings is very long, the construction sector faces different recycling challenges compared to those for short-lived goods. The long time between installation and recycling means that design for recycling, in principle, would need to consider the waste management situation of more than 50 years into the future. Technical, regulatory, and commercial considerations of recycling can be substantially different after the long timespan between installation and demolition.

Over such timeframes, for example, substantial changes can occur in terms of new recycling technologies becoming available, making 'recyclability' definitions difficult. At time of demolition, a material today considered not recyclable may indeed have become recyclable. Conversely, building materials may have experienced ageing effects when they are collected for recycling[44] that are substantially different from what is seen in short-lived products, reducing the viability of recycling.

In regulatory terms, chemical regulations may change, causing **demolition waste** to contain chemical substances considered at time of recycling to be 'legacy substances', no longer suitable for the inclusion into new materials.

Finally, for commercial reasons, takeback or deposit schemes are difficult to operate across multiple decades, considering, for example, inflation.

For the following, more detailed discussion, it is important to differentiate two types of 'construction waste', namely, **installation waste**, which comprises offcuts, residues and packaging materials, and **demolition waste.** As **installation waste**, other than packaging, in most cases does not contain adhesives, it will not be discussed here in detail.

It is also important to stress that the step of the actual recycling of a material is just one of multiple that need the be fulfilled for successful recycling to occur in practice. In particular, collection and sorting can strongly determine the achieved recycling rate, as only waste that is collected can be recycled and different materials must generally be separated before recycling. Selective deconstruction and sorting of waste at source are of key importance for high quality recycling as post-sorting is possible but the more mixed the initial stream, the more difficult the sorting becomes.

With all the above considerations in mind, the construction sector is already very successful at recycling many of its materials, including adhesive- and sealant-containing products and materials. The remainder of this section provides an overview of key demolition materials / waste streams and their recycling rates in Europe.

Mineral materials

Very high recycling rates are already achieved in the EU for mineral materials, with 70-80% in the EU overall as well as in large member states[45], [46].

Bricks and roof-tiles

Very high recycling rates are possible for bricks and rooftiles, for example, a recycling rate of approximately 77% in Germany in 2018[47]. Bricks and roof tiles are partly also already reused, particularly for restoration of historic buildings. Innovative approaches exist for the automatic cleaning of used bricks, removing mortar residues and thus obtaining clean bricks for reuse.[48]

Ceramics

Ceramics can typically end in recycling streams with other mineral wastes. Recycling in a closed loop is challenging for ceramics due to high requirements on performance and appearance of ceramic products. This impediment to recycling exists already on the level of the main ceramic material.

Steel

Steel is one of the most recycled materials worldwide. The recycling rate from demolition reached an average of 83% in Western Europe[40] in 2001 with examples of some countries at 90% and above[39]. Reuse of entire steel elements is practiced, with a reuse rate from demolition at an average of 14% in Western Europe in 2001[40]. In the recycling process (remelting), foreign materials, including any adhesives or sealants, are effectively removed.

Flat glass

Flat glass can be recycled at a high rate in open loop. For example, more than 80,000 tons of flat glass were collected for recycling in the Netherlands in 2020 and recycled at a rate of above 90%[49]. Non-glass components can be removed during pre-processing or may be removed or destroyed during glass recycling. Overall glass recycling rates are difficult to measure but a level of 90% is suggested to be possible by one study[50].

Due to very high requirements on optical purity, recycled flat glass is predominantly not used for glazing applications. Closed loop recycling to flat glass products does exist but still at low rates (20-26% of cullet in Europe[51]). The main uses of recycled flat glass are in insulation products and packaging[49].

Polyvinyl chloride (PVC)

The European VinylPlus network recycles about 700,000 tons of PVC annually, about 27% of the total available waste[52].

Very high recovery and recycling rates are possible for windows, doors and shutters, as demonstrated, for example, by the Rewindo system in Germany, which achieves an 85% recycling rate for PVC from window frames, roller shutters and doors[53].

Recycled quantities are lower for pipes and flooring materials. Recycling is possible but factors such as recoverability and contamination with soil or adhesive influence the outcome.

Insulation panels

When considering the recycling of insulation panels, a clear differentiation needs to be made between **installation waste** and **demolition waste**.

Installation waste (offcuts) is clean and therefore readily and widely recycled, with an overall 30% recycling rate in the EU in 2018[54].

When recycling **demolition waste**, cementitious material needs to be separated, which can be achieved mechanically[55]. Also, **demolition waste**, which may be decades old, may contain legacy substances, no longer allowed in the EU. Dissolution recycling for polystyrene and chemical recycling technologies for polystyrene and polyurethane foams are progressing and will offer additional opportunities for the removal of legacy substances and regeneration of monomers from foam waste.

Demolition waste is recycled less consistently with an overall 10% recycling rate in the EU in 2018[54]. Some countries, however, do reach installation waste levels of recycling, such as the example of the Czech Republic at 27%.

Wood

Construction and demolition activities can be very large sources of wood waste, for example, above 80% by weight in some parts of Austria, about 60% by weight in the UK, and about 40% by weight in Italy and Germany[56], [57].

Recycling rates differ widely but can reach high levels, for example, in Italy at above 80%, in France at around 65%[57].

Recycling of wood is a mechanical process and therefore must be open loop. The typical output of recycling of solid wood is chipboard and similar products. Alternative uses for wood wastes exist in the bioeconomy.

16 Adhesives and sealants in recycling processes

Due to their small weight percentage in any given item, adhesives and sealants are generally not the target of recycling[27]. Therefore, rather than being 'recyclable' themselves, adhesives and sealants primarily need to allow for the recycling of their substrate(s), i.e., the main construction materials.

Three principal approaches exist:

- **compatibility** with recycling, particularly where bonded substrates are mutually compatible in recycling
- (selective) **releasability**, where mechanical separation is feasible
- (induced) **debonding**, where mechanical separation is not feasible

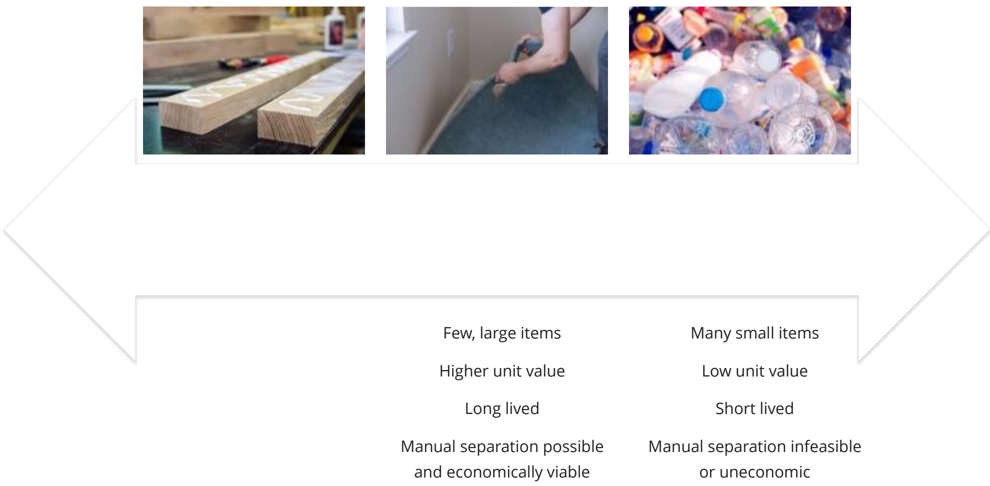

Figure 18: Different approaches for adhesives and sealants to support recycling.

Where adhesively bonded elements are of the same material, or mutually **compatible** in recycling, compatibility of adhesives and sealants with the relevant recycling processes can be the approach of choice. Examples include adhesives used in wood joinery or pipe sealants.

In addition to direct material **compatibility**, adhesive and sealants may also be removed after demolition, during recycling processes. Removal of adhesives and sealants from their substrates is possible, for example, by soaking or mechanical impact (milling, grinding). Post-release separation is then possible by density / weight (flotation, wind sifting, air elutriation) or by size (sieving).[44], [58]

As a Fraunhofer IFAM study on adhesives[27] describes, large component dimensions favour mechanical release of bonded joints, where necessary supported by suitable machinery. This **releasability** can be further improved upon by adhesive applications that provide selective release, i.e., the adhesive remains on a substrate where it is not detrimental to recycling (or reuse). Selective release can be found, e.g., in multilayer wallpapers which leave a clean layer on the wall that can immediately be wallpapered again or peelable mounting tapes (Figure 19).


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Figure 19: Mechanical removal of old wallpapers can include selective release to leave a clean surface.

Where mechanical separation is not feasible and adhesively bonded materials must be separated before recycling, **debonding** may offer solutions. It is important to bear in mind that a potential for **debonding**, designed into a product is not automatically realised. For all reversible bonds, ecological and commercial considerations determine whether **debonding** is actually realised. The highest realisation potential of debonding exists in reuse, as the aim is typically to recover a part in best possible condition.

In the case of recycling operations, as a general principle, the realisation potential of **debonding** depends on the substrates' value and composition: the highest potential typically is present in cases where both substrates are different from each other, both are individually valuable and both are of a relevant weight share in the overall item. Lesser amounts of a material different from the main material are more likely to be simply discarded, rather than recycled, unless highly valuable. A process may then target only the main material for recycling and rely on the ability to remove / sort out these minority materials after shredding, rather than through debondability. The example of waste furniture, held together by screws (a typically cited example of a reversible fastening) shows how screws will in practice not be removed through their 'debonding mechanism'. Rather, the whole item will be shredded, and screws and nails be removed magnetically. It is the metal screws sortability, i.e., their magnetism, not their debondability that makes them unproblematic for recycling. A plastic screw, equally debondable in principle, but not magnetically removable, may prove substantially more problematic.

Debonding can be achieved by soaking the bonded area in a suitable medium to weaken or dissolve the adhesive. A long-established example is wallpaper removal (Figure 20).

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Figure 20: Soaking of wallpapers for easier removal, a form of debonding.

Challenges for the recycling of adhesive and sealant containing materials remain where such removal is not sufficiently possible. Examples can be found in recycling of flooring materials: if too much adhesive remains on synthetic fibre carpets or vinyl flooring[59] and the adhesive residues are not sufficiently compatible with the recycling process, the quality of the recyclate is reduced.[9]

16.1 Recyclability of packaging for adhesives and sealants

Even though smaller in impact relative to the products themselves, the packaging of adhesives and sealants presents a further opportunity to improve sustainability. For the design and choice of packaging, the logic of the waste hierarchy (prevent – reduce – reuse – recycle) can be followed. In addition, the use of **renewable carbon** and recycled content can reduce the materials' footprint.

While certain packaging types require specific solutions, good recycling options already exist for most adhesives and sealants primary and secondary packaging formats. The remainder of this section provides an overview of the most common packaging formats.

17 Packaging types recycling in widely available infrastructure

Steel containers

Reuse is well established for designated steel containers; reuse of drums relies on emptiability, which may be aided by the use of flexible liners. Recycling of steel is well established with a very high steel recycling rate worldwide (70-90%)[60]. Recycled content is commonly high in steel, in Europe typically > 50 wt %[61].

PE and PP

Reuse of rigid containers is possible but not available in all locations. Recycling of emptied / washed packaging is possible where suitable infrastructure exists.[10] Recycled content can be possible,

[9] Multimaterial flooring products, for example, laminate flooring or multi-material carpets, may also require debonding of their constituent layers for successful recycling to occur. This is however not related to the deinstallation but is also true for installation waste.

[10] Certain limitations are to be observed based on residual contents, hazardous goods considerations; paper labels need to be removed before recycling.

depending on use case (hazardous goods regulations), with multilayer moulding increasing the options to use recyclate in inner layers.

Paper and board containers

Reuse is not common as cleaning of paper packaging is difficult. Recycling of paper is well established,[11] with typical recycling rates of above 60%[62]–[64]. Recycled content is high in most fibre-based products, typically above 50 wt %[64].

18 Special packaging cases

Plastic silicone cartridges

Residual silicone is considered by plastics recyclers to be a disruptor for standard PE / PP recycling processes. Dedicated collection and recycling systems can allow for the successful recycling of silicone cartridges.

PU foam cans

Separate collection is required, is in fact mandated by law, as material left in the packaging after use may be classified as hazardous goods. Collection and recycling schemes for PU foam cans are already implemented in practice[33].

Blister packs

The cardboard backing is generally recyclable; the PET thermoforms, however, are a challenge for PET recycling if paper fibres remain on the seal area; a clean release is required.

'Sausage packs' (and drum liners)

Sausage packs and drum liners are often multi-material multi-layer (MMML) flexible film structures, which today still exhibit low recycling rates in general. The high relative weight share of product residue after use is a further challenge for the recycling of flexible packaging compared to the recycling of rigids. The sustainability benefit of flexibles is therefore not provided through recyclability but through their low weight, outperforming rigids even at zero recycling rate[65],[66].

19 Quantifying environmental performance of adhesives and sealants

This section will explore how the environmental performance, the 'footprint', of adhesives and sealants can be quantified. While the majority of the section is dedicated to the footprint of these products themselves, the second part illustrates the importance of considering the net benefits of

[11] For coated, laminated, and siliconised paper depending on local infrastructure.

adhesives and sealants in conjunction with the construction materials they are used on and the use phase benefits they impart.

19.1 Quantifying the footprint of construction products

Environmental product declarations (EPDs) are a standardised way to communicate sustainability performance (Figure 21). EPDs are based on ISO 14025 'Environmental labels and declarations'. They are 'Type III environmental declarations' under this ISO norm, intended for business-to-business communication. EPDs are managed with 'programmes', that administer the creation, verification, and publication of EPDs. For construction, a key programme operator is *Institut Bauen und Umwelt e.V. (IBU)*.

While the ISO norm standardises EPDs as an objective communication of life cycle assessment (LCA)[12] results, different methodological choices are still possible for the LCA, which could lead to results that are not easily compared. Product category rules (PCRs), therefore, fix such methodological choices for a given product group. Fixing the parameters and endpoints of the LCA enables comparability of EPDs, which are generated based on the same PCR. Key PCRs for construction are EN 15804 and ISO 21930.

In addition to a 'standard EPD' which covers one product, EPD programmes can allow for the grouping of products into one EPD. A choice can be made for the calculation to use the average values of the products to be grouped ('average EPD') or the worst case of the products to be grouped ('model EPD').

The option to group products of several manufacturers allows, for example, an industry association to provide EPDs. Consequently, a number of model EPDs for adhesives and sealants[13] are offered by FEICA.[14] Each describes the maximum environmental impact of a well-defined group of adhesive / sealant products and provides verified footprint information for adhesives and sealants on a cradle-to-gate scope, including the carbon footprint and multiple further indicators.

The openly accessible model EPDs (Sector EPDs) allow the contributions of adhesives and sealants to the environmental performance of finished construction products to be calculated by construction products manufacturers.

The model EPDs, however, do not describe impacts or benefits during the use phase of the building such as thermal insulation, durability increase and extended lifetime. Such benefits (e.g., insulation) can be contained in EPDs of the finished construction product (e.g., a window) if the use phase is declared.[15]

Similarly, the comparison of adhesives and sealants with alternative technologies is possible only on the basis of a finished construction product design.

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[12] According to ISO 14040 and ISO 14044.
[13] https://www.feica.eu/our-projects/epds.
[14] The Association of the European Adhesive & Sealant Industry.
[15] The calculation of such benefits also typically requires the declaration of a functional unit (e.g., covering a given area of a façade), rather than a weight-based calculation.

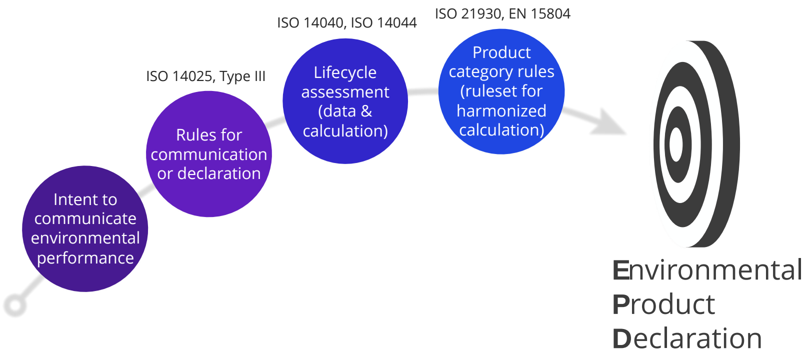

Figure 21: Illustration of the pathway to an Environmental Product Declaration.

The 2011 EU Single Market for Green Products initiative led to a proposal of new sustainability metrics[67], namely the Product Environmental Footprint (PEF) and the Organisation Environmental Footprint (OEF). The approach considered the use of PEF and OEF as the basis for labelling requirements for final products that are sold to consumers.

A pilot phase of the PEF project ran till 2018, to develop the methodology and create a number of category rules. These included several categories related to construction. For adhesives and sealants, 'insulation' is the most relevant.

Improvements options[68] and harmonisation gaps with the EPD system[69] have since been identified and work has already been undertaken on harmonisation, e.g., on compatibility of EN 15804 with the PEF approach. Such harmonisation would be desirable as it would allow the use of existing (model) EPDs as data sources for the PEF.

Figure 22: Comparison of the PEF and the EPD declaration systems.

19.2 Importance of the net footprint benefits of adhesives and sealants

While, undoubtedly, adhesives and sealants carry their own footprint due to their raw materials, their production and their logistics, it should be considered that the amount of adhesive or sealant in a final product is very low (in construction often less than one weight percent of a building). The **embodied carbon** added by adhesives and sealants to buildings is therefore minimal. At the same time, considering only the footprint of the adhesive or sealant would miss the large positive environmental performance benefits of final products that are possible only with adhesives and sealants. To understand the true benefits of adhesives and sealants, the focus should therefore be on the finished product[27].

While the exact savings are subject to the specific products and thus beyond the scope of this report, a general observation related to adhesives and sealants can be made: enabling in-use savings (for example, through improved thermal insulation) or allowing for the design of a more sustainable finished product[16] can rapidly offset the full footprint of adhesives and sealants[23], [70]. The carbon footprint break-even point, as illustrated in Figure 23, for adhesives and sealants can occur within days of installation, providing a compelling case for their use.

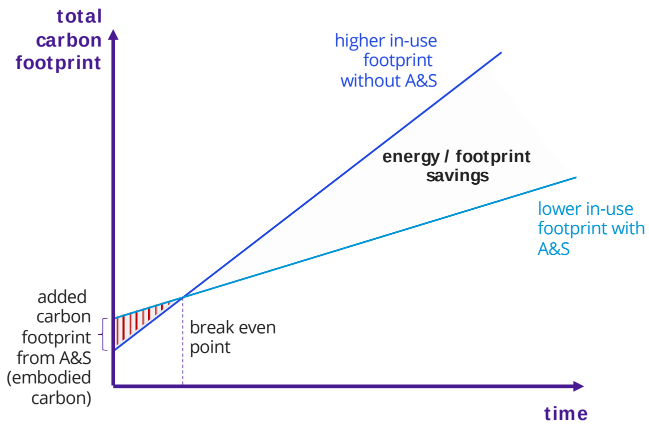

Figure 23: Evolution of total carbon footprint over time with and without adhesives and sealants.

[16] For example, through a weight saving; see section on material efficiency.

20 Conclusion

Adhesives and sealants present numerous benefits to the construction sector (Figure 24). When used in the manufacture of construction products and/or in the construction of a building itself, they help improve **energy efficiency** through insulation and enable **material efficiency** through material reduction and/or the use of more sustainable materials. During the lifetime of the building, they support maintenance, repair and renovation and can thereby increase a building's durability. As evidenced by the high recycling rates of demolition waste, with the right design, adhesives and sealants do allow for and enable **circularity** and thereby increase **material efficiency** further.

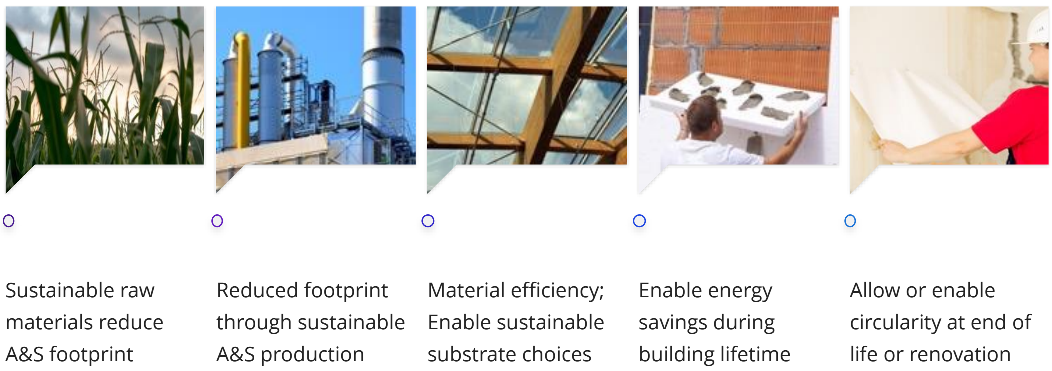

Figure 24: Summary of contributions of adhesives and sealants to sustainability in the construction sector.

Challenges and risks for adhesives and sealants remain on the basis of the perception that they prevent repair, reuse and recycling and because, simultaneously, the full-life-cycle savings enabled by adhesives and sealants are not always immediately visible. Addressing specific existing challenges in recycling and reuse could therefore help to further improve the position of adhesives and sealants in the construction sector.

Contact

FEICA Regulatory Affairs:
Dimitrios Soutzoukis (d.soutzoukis@feica.eu)

FEICA is registered in the **EU Transparency Register** with ID no. **51642763262-89**

FEICA - Association of the European Adhesive & Sealant Industry
Rue Belliard 40 box 10, 1040 Brussels, Belgium
Tel: +32 (0)2 896 96 00
info@feica.eu | www.feica.eu

Publication ref.: RAM-IN-L05-031

References

[1] 'In focus: Energy efficiency in buildings'. European Commission, 2020. Accessed: Mar. 29, 2022. [Online]. Available: https://ec.europa.eu/info/news/focus-energy-efficiency-buildings-2020-lut-17_en.

[2] 'Study on circular economy principles for buildings' design', European Commission, 2021.

[3] D. Thelen *et al.*, 'Scaling the Circular Built Environment', wbcsd, 2018.

[4] 'The European Green Deal'. European Commission, 2019.

[5] *REGULATION (EU) 2021/1119 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law')*.

[6] 'Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL establishing a framework for setting ecodesign requirements for sustainable products and repealing Directive 2009/125/EC'. European Commission, 2022.

[7] *Regulation (EU) No 305/2011 of the European Parliament and of the Council of 9 March 2011 laying down harmonised conditions for the marketing of construction products and repealing Council Directive 89/106/EEC*.

[8] 'A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives'. European Commission, 2020.

[9] 'Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the energy performance of buildings (recast)'. European Commission, 2021.

[10] *Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 Establishing a Scheme for Greenhouse Gas Emission Allowance Trading Within the Community and Amending Council Directive 96/61/EC*. 2005. doi: 10.1017/CBO9780511664885.043.

[11] 'Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Directive 2003/87/EC establishing a system for greenhouse gas emission allowance trading within the Union, Decision (EU) 2015/1814 concerning the establishment and operation of a market stability reserve for the Union greenhouse gas emission trading scheme and Regulation (EU) 2015/757'. European Commission, 2021.

[12] 'Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL establishing a carbon border adjustment mechanism'. European Commission, 2021.

[13] *REGULATION (EU) 2020/852 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 18 June 2020 on the establishment of a framework to facilitate sustainable investment, and amending Regulation (EU) 2019/2088*. 2020.

[14] 'A sustainable bioeconomy for Europe: strengthening the connection between economy, society and the environment Updated Bioeconomy Strategy'. European Commission, 2018.

[15] *DIRECTIVE 2008/98/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 19 November 2008 on waste and repealing certain Directives*.

[16] J. Vermeulen, 'EU Construction & Demolition Waste Management Protocol', European Commission, 2016.

[17] 'LEVEL(S): A common language for building assessment'. European Commission, 2021.

[18] 'LEVEL(s): Putting whole life carbon principles into practice'. European Commission, 2021.

[19] 'EU Principles for Sustainable Raw Materials'. European Commission, 2021.

[20] 'Forging a climate-resilient Europe - the new EU Strategy on Adaptation to Climate Change'. European Commission, 2021.

[21] S. Lechtenböhmer and A. Schüring, 'The potential for large-scale savings from insulating residential buildings in the EU', *Energy efficiency*, vol. 4, no. 2, pp. 257–270, 2009.

[22] 'External Thermal Insulation Composite Systems (ETICS)'. https://www.feica.eu/information-center/good-practices/construction-i (accessed Mar. 30, 2022).

[23] 'Elastic joint sealants for tight building envelopes'. https://www.feica.eu/information-center/good-practices/construction-iii (accessed Mar. 30, 2022).

[24] 'Adhesives and sealants for high performance insulating windows'. https://www.feica.eu/information-center/good-practices/construction-vi (accessed Mar. 30, 2022).

[25] 'Adhesives for high performance structural glazing for building facades'. https://www.feica.eu/information-center/good-practices/construction-ii (accessed Mar. 30, 2022).

[26] M. Röck *et al.*, 'Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation', *Applied Energy*, vol. 258, p. 114107, Jan. 2020, doi: 10.1016/j.apenergy.2019.114107.

[27] 'Kreislaufwirtschaft und Klebtechnik', Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM, 2020.

[28] 'Cutting greenhouse gas emissions through circular economy actions in the buildings sector', European Environment Agency, 2020.

[29] X. Le Den *et al.*, 'The Decarbonisation Benefits of Sectoral Circular Economy Actions', Ramboll, Fraunhofer ISI, ecologic, 2020.

[30] 'Adhesives for timber construction'. https://www.feica.eu/information-center/good-practices/construction-v (accessed Mar. 30, 2022).

[31] 'Adhesives for lightweight furniture'. https://www.feica.eu/information-center/good-practices/woodworking (accessed Mar. 30, 2022).

[32] M. Carus, L. Dammer, A. Raschka, and P. Skoczinski, 'Renewable Carbon: Key to a Sustainable and Future-Oriented Chemical and Plastic Industry: Definition, Strategy, Measures and Potential'. nova-Institut, 2020.

[33] 'Recycling PU foam in pressurised containers'. https://www.feica.eu/information-center/good-practices/construction (accessed Mar. 30, 2022).

[34] Z. Kapetaki, European Commission, and Joint Research Centre, *Carbon capture utilisation & storage: technology development report 2020*. 2020. Accessed: Apr. 07, 2021. [Online]. Available: https://op.europa.eu/publication/manifestation_identifier/PUB_KJBK21003ENN

[35] T. Czigler, S. Reiter, P. Schulze, and K. Somers, 'Laying the foundation for zero-carbon cement'. McKinsey & Company, 2020.

[36] L. Tercero Espinoza, L. Rostek, A. Loibl, and D. Stijepic, 'The Promise and Limits of Urban Mining', Fraunhofer ISI, 2020.

[37] European Academies Science Advisory Council and Secretariat, 'Decarbonisation of buildings: for climate, health and jobs', easac, 2021. Accessed: Jul. 06, 2021. [Online]. Available: http://nbn-resolving.org/urn:nbn:de:gbv:3:2-137698

[38] 'Scenarios for a transition pathway for a resilient, greener and more digital construction ecosystem'. European Commission, 2021.

[39] 'Stahlrecycling im Bauwesen', Bergische Universität Wuppertal, 2014.

[40] M. Sansom and J. Meijer, 'Life-cycle assessment (LCA) for steel construction', European Commission, 2002.

[41] P. Hradil, A. Talja, M. Wahlström, S. Huuhka, J. Lahdensivu, and J. Pikkuvirta, 'Re-use of structural elements', VTT, 2014.

[42] A. M. G. Coelho, R. Pimentel, V. Ungureanu, P. Hradil, and J. Kesti, 'European Recommendations for Reuse of Steel Products in Single-Storey Buildings', ECCS – European Convention for Constructional Steelwork, 2020.

[43] 'Affordable housing initiative'. https://ec.europa.eu/growth/sectors/proximity-and-social-economy/social-economy-eu/affordable-housing-initiative_en (accessed Mar. 30, 2022).

[44] D. Eckert, R. Kocina, and D. H. Achenbach, 'Förderung einer hochwertigen Verwertung von Kunststoffen aus Abbruchabfällen sowie der Stärkung des Rezyklateinsatzes in Bauprodukten im Sinne der europäischen Kunststoffstrategie', Umweltbundesamt, 2021.

[45] 'Emerging Challenges of Waste Management in Europe - Limits of Recycling', Trinomics, 2020.

[46] 'Mineralische Bauabfälle Monitoring 2018', Kreislaufwirtschaft Bau, 2021.

[47] 'Re-Use und Recycling von Ziegeln'. http://www.ziegel.de/recycling (accessed Mar. 30, 2022).

[48] 'Rebrick'. http://www.gamlemursten.eu/ (accessed Mar. 30, 2022).

[49] 'Jaarverslag 2020', Vlakglas Recycling Nederland, 2021.

[50] 'Forschungsbericht Recycling von Flachglas im Bauwesen - Analyse des Ist-Zustandes und Ableitung von Handlungsempfehlungen', ift Rosenheim, 2019.

[51] 'Flat glass in climate-neutral Europe'. Glass for Europe, 2020.

[52] 'REPORTING ON 2020 ACTIVITIES and summarising the key achievements of the past 10 years'. vinylplus, 2021.

[53] 'kunststofffenster-recycling in zahlen 2020'. Rewindo, 2021.

[54] 'Waste generation, waste streams and recycling potentials of HBCD- containing EPS/XPS waste in Europe and forecast model up to 2050'. conversio, 2020.

[55] 'PolyStyreneLoop - EUMEPS Construction'. https://eumeps.construction/circular-economy/polystyreneloop (accessed Mar. 30, 2022).

[56] S. Flamme, S. Hams, J. Bischoff, and C. Fricke, 'Evaluierung der Altholzverordnung im Hinblick auf eine notwendige Novellierung', Umweltbundesamt, 2020.

[57] 'Absorbing the Potential of Wood Waste in EU Regions and Industrial Bio-based Ecosystems', BioReg, 2018.

[58] 'Potenziale eines hochwertigen Recyclings im Baubereich', VDI, 2016.

[59] 'Recofloor Material Specifications', *Recofloor*. https://www.recofloor.org/material-specification/ (accessed Mar. 30, 2022).

[60] 'Metal Stocks & Recycling Rates', United Nations Environment Programme, 2011.

[61] 'The Recycled Content of Steel for Packaging', APEAL, 2017.

[62] 'ICFPA 2020–2021 Sustainability Progress Report', ICFPA, 2021.

[63] 'Key Statistics 2020 European Pulp & Paper Industry', cepi, 2021.

[64] 'Corrugated Packaging – A Recycling Success Story', Corrugated Packaging Alliance, 2016.

[65] F. Wellenreuther, 'Resource Efficient Packaging', ifeu, 2016.

[66] 'Resource Efficiency - Prevention - Flexible Packaging Europe'. https://www.flexpack-europe.org/resource-efficiency-prevention (accessed Mar. 30, 2022).

[67] 'COMMISSION RECOMMENDATION of 9 April 2013 on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations'. European Commission, 2013.

[68] European Commission. Joint Research Centre., 'Suggestions for updating the Product Environmental Footprint (PEF) method', European Commission. Joint Research Centre, 2019. Accessed: Feb. 08, 2022. [Online]. Available: https://data.europa.eu/doi/10.2760/265244

[69] V. Durão, J. D. Silvestre, R. Mateus, and J. de Brito, 'Assessment and communication of the environmental performance of construction products in Europe: Comparison between PEF and EN 15804 compliant EPD schemes', *Resources, Conservation and Recycling*, vol. 156, p. 104703, May 2020, doi: 10.1016/j.resconrec.2020.104703.

[70] B. Brandt, E. Kletzer, H. Pilz, D. Hadzhiyska, and P. Seizov, 'Silicon-Chemistry Carbon Balance: an Assessment of Greenhouse Gas Emissions and Reductions'. denkstatt / Global Silicones Council, 2012.