🏆 *reviewed paper*

# The Potential of Bio-Based Insulation Materials for Healthy Living Spaces and Sustainable Architecture

*Sandra Böhm*

(Dipl. Des. Sandra Böhm, KIT, Faculty of Architecture, Institute of Design and Building Technology IEB, Sustainable Construction, Englerstraße 11, 76131 Karlsruhe, sandra.boehm@kit.edu)

## 1 ABSTRACT

In Germany, 30 % of $CO_2$ emissions and 35 % of final energy consumption are due to the operation of buildings.[1] The building sector must therefore make an intensive contribution to the energy transition. In addition to the requirement to operate every new heating system with 65 % renewable energies from January 2024, the energy-efficient refurbishment of existing buildings, for example by installing new windows or upgrading thermal insulation, is to be massively promoted in order to reduce energy consumption and emissions. The renovation of the building stock should contribute significantly to the EU's goal of climate neutrality by 2050. In order to achieve a climate-neutral building stock, the operating energy and in particular the non-renewable share of primary energy must be drastically reduced and the remaining energy demand must be covered predominantly with renewable energy sources.[2] A large part of the operating energy of buildings is due to the heating or cooling systems in living spaces. Appropriate building insulation, especially in existing buildings, can save energy at this point. Do we want to continue this energy upgrade of our buildings with synthetic materials from finite resources, some of which have been proven to endanger our health, or will we succeed in the biological insulation turnaround that would bring energy-efficient, sustainable and healthy living spaces? With a view to the desired climate neutrality of the EU, is it not a logical conclusion to refurbish the building stock with insulation materials that consume as little energy as possible in their production, while causing virtually no emissions?

In answering these questions, it is important to consider the potential of biological insulation materials. What raw materials are available? What are the manufacturing processes? How are the material properties and durability of biological insulation materials to be assessed?

The paper examines biological insulation materials and their use for creating healthy living spaces in a sustainable architecture. It focuses on the raw material base, which often consists of residues and by-products, the construction-relevant properties and aspects of material health. Depending on the results of this analysis, the aim is to define the use of biological insulation materials as part of a sustainable resource management in the building sector, which can be understood as a Nature-Based Solution. According to the definition of the International Union for Conservation of Nature (IUCN) Nature-Based Solutions (NBS) are described as measures for the protection, sustainable management and restoration of natural and modified ecosystems.[3]

The following explanations are intended to show that the replacement of synthetic insulation materials, some of which contain substances that are harmful to health, with 100 % bio-based insulation materials can help to conserve non-renewable resources and thus combat the scarcity of resources. The mostly very environmentally damaging mining methods of non-renewable resources could be greatly reduced and, in this way, ecosystems could be protected. In addition, the increased use of renewable resources could positively address other challenges within the construction industry, such as the need to create healthy living spaces and drastically reduce emissions from the production of building materials.

Keywords: sustainable architecture, renewable raw materials, alternative resources, healthy building materials, bio-based insulation materials

[1] Umweltbundesamt, UBA (Federal Environment Agency): Energiesparende Gebäude (2022). URL: https://www.umweltbundesamt.de/themen/klima-energie/energiesparen/energiesparende-gebaeude#gebaude- important-for-climate-protection [Accessed: 03.05.2023]

[2] Umweltbundesamt, UBA (Federal Environment Agency)(ed.): Klimaneutraler Gebäudebestand 2050. Energieeffizienzpotentiale und die Auswirkungen des Klimawandels auf den Gebäudebestand. Dessau- Roßlau, November 2017. URL: https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2017-11-06_climate-change_26-2017_klimaneutraler- gebaeudebestand-ii.pdf [Accessed: 30.05.2023]

[3] International Union for Conservation of Nature (IUCN): About Nature-based Solutions. URL: https://www.iucn.org/our-work/nature-based-solutions [Accessed: 01.03.2023]

## 2 INSULATING MATERIALS ON THE MARKET

A survey by the Agency for Renewable Resources (Fachagentur Nachwachsende Rohstoffe e. V., FNR) identified the market shares of the most commonly used insulation materials. Insulation materials based on fossil raw materials had the largest market share of insulation sales in 2019 with 48 %.Mineral insulation materials had a share of 43 %. Insulation materials made from renewable raw materials were only sold at 9 % in 2019 (2 % more than in 2011). However, manufacturers are noticing an upward trend.[4] Finally, the topic of sustainable construction has also arrived in society, so that more and more building owners are making a more conscious choice of materials when building a house or renovating an existing building.

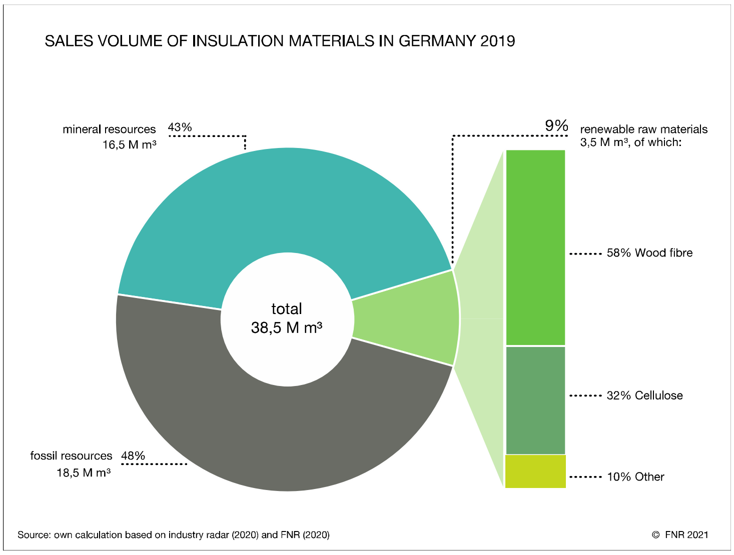


Fig. 1: Sales volume of insulation materials in Germany 2019. Source: Fachagentur Nachwachsende Rohstoffe e. V., FNR (Agency for Renewable Resources): Aktuelle Nachricht, 24.02.2021. Marktanteil von Nawaro-Dämmstoffen wächst. URL: https://www.fnr.de/presse/pressemitteilungen/aktuelle-mitteilungen/aktuelle-nachricht/marktanteil-von-nawaro-daemmstoffen-waechst [Accessed: 14.06.2023]. Translated and traced by Sandra Böhm and Luca Diefenbacher

In 2017, Pforzheim University published a market and social research study on the very low market share of insulating materials made from renewable raw materials, but also on their potential for further development. The Pforzheim University of Applied Sciences summarises the results of the study on its website and addresses a change from the “attitude-behaviour gap” to the “producer-people gap”.[5] In the past, building owners often had a positive attitude towards bio-based insulation materials, but did not act on their attitude. Today, however, according to the study, they would very much act according to their attitude and buy insulation materials made from renewable raw materials, but they are prevented from doing so by a lack of supply on the market. The main focus was on bio-based façade insulation, for example from wood fibres, cellulose or hemp. This study on “Renewable raw materials in the industry” is based on 340 interviews with private building owners, specialised companies, authorities, traders and architects.

A statement on the study emphasises the special role of architects as independent, advising and competent protagonists of the building sector. However, the manufacturing companies should lose their shyness about investments in research and development of insulating materials made from renewable raw materials, as the insulating materials sector plays a decisive role for the "ecological development" in Germany.[6]

[4] Fachagentur Nachwachsende Rohstoffe e. V., FNR (Agency for Renewable Resources): Marktanteil von NawaRo-Dämmstoffen wächst, Umfrage zum Einsatz biobasierter Baustoffe (2021). URL: https://www.fnr.de/presse/pressemitteilungen/aktuelle-mitteilungen/aktuelle-nachricht/marktanteil-von-nawaro-daemmstoffen-waechst [Accessed: 19.05.2023]

[5] Hochschule Pforzheim (Pforzheim University): From the Attitude-Behaviour-Gap to the Producer-People-Gap. 2018. https://www.hs- pforzheim.de/news_detailview/news/vom_attitude_behaviour_gap_to_the_producer_people_gap_1 [Accessed: 13.05.2023]

[6] Bundesministerium für Ernährung und Landwirtschaft (Federal Ministry of Food and Agriculture): Akzeptanz von Baumaterialen aus nachwachsenden Rohstoffen. 2018. URL: https://www.waldkulturerbe.de/aktuelles/aktuelles/akzeptanz-von-baumaterialen-aus-nachwachsenden-rohstoffen [Accessed: 30.05.2023]

The desire for more ecological insulation materials on the part of building owners is therefore present. The range of products on offer in the trade should be expanded accordingly. Some biological insulation materials already exist, some of them have been used for centuries, but they have been pushed out of the market by the development of modern synthetic materials. Today we realise that these synthetic materials are not the solution in the long run. The corresponding resources are coming to an end and their disposal is partly highly problematic - to name only two aspects relevant for the life cycle. In the following, exemplary insulating materials on a biological, synthetic and mineral basis will be presented and comprehensively compared with each other. The aim is to obtain an initial overview of possible potentials of biological insulation materials.

## 2.1 Origin and availability of raw materials and the production of insulation materials

### 2.1.1 Biological insulation materials from residues and by-products

Insulation materials made from renewable raw materials should be produced from domestic or regionally available resources in order to keep transport costs and the associated CO2 emissions as low as possible. In addition to the main raw material, however, different and partly synthetic additives are also added to bio-based insulation materials. These are intended to improve fire protection, prevent mould or pest infestation or stabilise the fibre structure of the insulation material. In order to obtain a recyclable biological insulating material, however, it is essential to do without such additives during production. If the insulation materials are100 % biological, they could be composted in one's own garden.

In addition to the flawless processing of renewable raw materials into building materials while avoiding harmful and/or synthetic substances, the efficient use of these raw materials is particularly relevant in protecting our ecosystems. Even renewable raw materials are not available in unlimited quantities. The raw material base of bio-based insulation materials consists, for example, of wood chips, flax fibres, cellulose flakes, straw, seaweed or cork scrap. These are residual materials and by-products from other material flows. Flax short fibres, for example, are a by-product of the textile industry. Seaweed accumulated on the coast is often removed at great expense and disposed of in landfills, as it is considered a nuisance on the beaches, which are mostly used for tourism, and is regarded as waste. However, these residual materials, which accumulate anyway, can be further processed into pressure-resistant boards, flexible mats, blow-in or plug-in insulation and used for building insulation.

Fig. 2: Accumulated seaweed in the Baltic Sea. Source: Lübecker Nachrichten: Seegras war früher ein Nebenverdienst für viele Fischer. URL: https://www.ln-online.de/lokales/nordwestmecklenburg/seegras-war-frueher-ein-nebenverdienst-fuer-viele-fischer-ESLCPAW7PUEGKZWUAEHEBMBWS4.html [Accessed: 14.06.2023], Copyright Foto: Maik Freitag.

In addition to the raw materials and additives used, the primary energy used in the manufacturing process plays a decisive role in assessing the sustainability of building materials. The use of insulation materials should reduce energy consumption in the use phase. With regard to the overall energy balance, it also makes sense to use insulation materials that are produced with as little energy as possible.

The following will discuss these aspects in more detail based on the selected insulation materials. Wood fibre insulation boards, a cellulose fibre blow-in insulation material, insulation fleeces made of flax and hemp are being compared with rock wool as a representative of mineral insulation materials and foamed polystyrene and PUR rigid foam insulation boards as representatives of fossil-based insulation materials. In addition, seaweed is presented as a niche product within the insulation industry.


ISBN 978-3-9504945-2-5. Editors: M. SCHRENK, V. V: POPOVICH, P. ZEILE, P. ELISEI, C.BEYER, J. RYSER, H. R. KAUFMANN – Ljubljana, Slovenia

Wood fibre insulation boards are made from residual wood from the sawmill industry. An insulation board consists of at least 80 % wood fibres.[7] It has a thermal conductivity of 0.040 W/(mK) and building material class B2, normally flammable. The wood information service describes the production of wood fibre insulation boards using the wet process as a process in which no additional binding agents are needed, as only the wood's own binding forces in the form of lignin come into play. The wood fibres are first thermo-mechanically broken down and finally set under heat. Wood fibre insulation boards are dried at 160 and 220 °C. Additives containing resin or bitumen are added to individual products to improve their strength, for example.[8]

The process data set of wood fibre insulation board (wet process) of Ökobaudat, refers also to the use of various additives, e.g. to PVAC (polyvinyl acetate), a plastic used in glues. Paraffin is also mentioned, which is used in special products to produce a water-repellent layer. So, you have to look closely and consider additives product by product. The recycling of residual materials, in this case wood chips, into a high-performance insulation material is particularly useful, but the total non-renewable primary energy demand (PENRT) in the production (module A1-A3) of wood fibre insulation boards from the wet process is very high (through the drying process) at 1823 MJ per m3 compared to other bio-based insulation materials.[9]

Cellulose insulation flakes are produced from waste paper with comparatively little manufacturing energy. The total non-renewable primary energy demand (PENRT) in production (module A1-A3) is 94.79 MJ per m³.[10] The insulation material has a thermal conductivity of 0.037 to 0.045 W/(mK) and is normally flammable (building material class B2). If the cellulose insulation is properly and tightly stuffed, a dense structure is created which prevents the spread of fire and on which a protective layer of carbon is formed.[11] Nevertheless, borates are added to the recycled fibres for fire and glow protection. Boric acid and borax were classified by the European Commission in 2010 as toxic to reproduction and as a substance of very high concern.[12] If the mixture contains more than 5 % borax or boric acid, it would ultimately have to be classified as well. The quantities actually added are even higher, for example 12 % borax and 8 % boric acid.[13]

When installing the flakes, a high dust load can occur, which is why work should only be carried out professionally with appropriate equipment and comprehensive cleaning of the construction site afterwards. There is no special occupational safety labelling for cellulose fibres, but the added borates are also contained in the dust. In the meantime, more compatible flame retardants are used, such as ammonium polyphosphate, which is classified by the Federal Environment Agency (Umweltbundesamt, UBA) as unproblematic in application.[14] With regard to the availability of the raw material, the relatively simple production and the physical building properties, blow-in insulation made of cellulose flakes is a good alternative to established synthetic insulation materials. However, they should not be used carelessly and special attention should be paid to professional installation and, if possible, borate-free mixtures should be used.

[7] Wolfgang Linden, Iris Marquardt (eds.): Ökologisches Baustofflexikon (Ecological Building Material Lexicon), Ökologisches Baustofflexikon. Bauprodukte, Chemikalien, Schadstoffe, Ökologie, Innenraum. 4th completely revised and expanded edition (2018). Berlin, Offenbach: VDE Verlag GmbH. Page 254

[8] Verband Holzfaserdämmstoffe (ed.): Informationsdienst Holz: Holzfaserdämmstoffe. Revised 3rd edition, 2018, Wuppertal. Page 5

[9] Ökobaudat: Prozess-Datensatz: Holzfaserdämmplatte (Nassverfahren) (de) ende. URL: https://oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=393f494d-8738-4330-aa5e-1652bb29b574&version=20.19.120&stock=OBD_2021_II&lang=de[Accessed: 01.06.2023]

[10] Ökobaudat: Prozess-Datensatz: Zellulosefaser Einblas-Dämmstoff(en) en de. URL. https://oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=c355d75b-9026-4899- a41c-e5d221c424f2&version=20.19.120&stock=OBD_2021_II&lang=de [Accessed: 01.06.2023]

[11] Fachagentur Nachwachsende Rohstoffe e. V., FNR (Agency for Renewable Resources) (ed.): Marktübersicht. Dämmstoffe aus nachwachsenden Rohstoffen. 10 revised edition, 2019, Gülzow-Prüzen

[12] WECOBIS Ökologisches Baustoffinformationssystem (Ecological Building Materials Information System): Borate, Überblick. URL: https://www.wecobis.de/service/sonderthemen-info/svhc-fsm-info/svhc-borate-info.html [Accessed: 30.05.2023]

[13] Wolfgang Linden, Iris Marquardt (eds.): Ökologisches Baustofflexikon (Ecological Building Material Lexicon), Ökologisches Baustofflexikon. Bauprodukte, Chemikalien, Schadstoffe, Ökologie, Innenraum. 4th completely revised and expanded edition (2018). Berlin, Offenbach: VDE Verlag GmbH. Page 115

[14] Ibid.

Flax insulation boards or flax fleece consist of short fibres of the flax plant. These short fibres are a by-product of the textile industry. The cultivation of flax is in sharp decline in Germany, but is being further expanded in neighbouring countries. The cultivation and harvesting of flax are labour-intensive, but almost all parts of the plant can be processed into different products.

 

Fig. 3 (left): Cellulose insulation. Source Fig. 3: Bio-Solar-Haus® GmbH: Zellulosedämmung URL: https://www.bio-solar-haus.de/ratgeber/zellulosedaemmung [Accessed: 14.06.2023], Fig. 4 (right): Flax dew roasting in the field. During dew roasting, undesirable substances are broken down by bacteria and fungi. Source: Wikipedia: Flachsfaser. URL: https://de.wikipedia.org/wiki/Flachsfaser, Copyright Foto: Rilegator - Eigenes Werk, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=14690380[Accessed: 14.06.2023]

Flax insulation boards have a thermal conductivity of 0.040 to 0.045 W/(mK) and are classified as normally flammable (building material class B2). The fibres are glued with starch or mixed with bicomponent plastic fibres. These bicomponent plastic fibres consist of either petroleum-based plastics or bioplastics. As with insulating materials made of cellulose, fire protection is also achieved by adding ammonium polyphosphates or borates. In some cases, soda ash is also used as an alternative.[15] In principle, the composition must also be taken into account, depending on the product. Against the background of recycling or possible later composting, insulation boards mixed with plastic should not be used. However, it can be said that a residual material that is available anyway is put to a sensible use. Some manufacturers take back the insulation boards after use for reuse or recycling. For example, material that is not damaged or soiled can simply be reused or processed into stuffing wool.[16] Loose flax insulation materials are also offered without additives and can be used as insulation material without any problems. They are naturally resistant to pests and resistant to mould.

Hemp insulation mats or hemp fleece consist of various parts of the hemp plant, especially the hemp fibre, have a thermal conductivity of 0.040 to 0.045 W/(mK) and are classified as normally flammable (building material class B2). The fibres are mixed with bicomponent plastic fibres. In some cases, supporting fibres made of starch are also used, but this process is still very cost-intensive. For fire protection, ammonium polyphosphates or soda are added. If handled properly, the flame retardants are considered harmless, but there is still potential for savings here. Material that has been used purely for this purpose is sometimes taken back by the manufacturers to be used in the production of new boards or stuffing wool. Undamaged mats can simply be reused.[17] The availability of hemp fibre from Germany is currently very limited, as the cultivation of hemp fibre has only been permitted under strict conditions since 1996. In the meantime, however, one can observe an upward trend in the expansion of cultivated areas for this undemanding and versatile plant.[18]

Despite the still limited availability of hemp and flax products in Germany, these rapidly renewable fibre plants should not be underestimated. Due to the versatility of the high-performance fibres, they will certainly play a greater role in our country again in the future. What is striking about both products is the high non-

[15] Ökobaudat: Prozess-Datensatz: Flachsvlies (en) en de. URL: https://oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=af13e5a8-0961-454a-ad3a-7093a37fc802&version=20.19.120&stock=OBD_2021_II&lang=de [Accessed: 30.05.2023]

[16] Wolfgang Linden, Iris Marquardt (eds.): Ökologisches Baustofflexikon (Ecological Building Material Lexicon), Ökologisches Baustofflexikon. Bauprodukte, Chemikalien, Schadstoffe, Ökologie, Innenraum. 4th completely revised and expanded edition (2018). Berlin, Offenbach: VDE Verlag GmbH. Page 185

[17] ibid., p. 240.

[18] Bundesinformationszentrum Landwirtschaft: Welches Potenzial hat Hanf als Nutzpflanze? (2022) URL: https://www.landwirtschaft.de/landwirtschaft-verstehen/wie-arbeiten-foerster-und-pflanzenbauer/welches-potenzial-hat-hanf-als-nutzpflanze [Accessed: 13.05.2023]

renewable primary energy demand in production (module A1-A3) with about 1500 MJ per m³.[19] There is certainly still potential for savings here.

Jute insulation boards are made from old cocoa or coffee sacks that were previously used to transport goods to Germany and may not be used again for the same purpose.[20] They have a thermal conductivity of 0.038 to0.041 W/(mK) and are classified as normally flammable (building material class B2). Up to 10 % biopolymeric support fibres are added for stabilisation and up to 5 % soda ash for fire protection.[21] The soda is already used for cleaning the shredded fibres. The insulation boards can be installed very easily and quickly by the user without special protective clothing. The boards can be assembled by the customer or delivered prefabricated. Like many natural insulating materials, jute insulation boards have a high absorption capacity and can compensate moisture well due to this property. After absorbing moisture, they do not lose their function as long as the moisture can be released again.[22] In addition, they offer particularly good heat protection in summer.


Fig. 5 (left): Thermal insulation from used coffee or cocoa sacks made from jute fibre. Source: mb-netzwerk GmbH, Portal Ökologisch Bauen: Jutedämmung, Wärmedämmung aus Jute. URL: https://www.oekologisch-bauen.info/baustoffe/naturdaemmstoffe/jutedaemmung/, Copyright Foto: Thermo Natur GmbH & Co. KG [Accessed: 14.06.2023].
Fig. 6 (right): Washed-up Neptune balls on a Mediterranean beach. Source: NeptuGmbH: Was ist NeptuTherm®, woher kommt und wie entsteht es? URL: http://neptusan.com/was-ist-neptutherm.html, Copyright Foto: NeptuGmbH [Accessed: 14.06.2023]

Naturally occurring residues that do not come from agriculture or an already existing production lines represent further interesting resources for material recycling. Seaweed is also such a natural residual material, particularly well suited for the production of insulation materials. However, insulation materials made from seaweed have been used by the local population for a long time and are naturally suitable for use in the construction sector they are still absolute niche products.

Two different species of seaweed are used for the production of insulation materials. Common sea grass (Zostera marina) grows at a depth of 14 m in the form of meadows along the Baltic Seacoast. The blades of grass die in autumn and are washed up on the coasts in large quantities. Due to its availability and beneficial properties, it has been used for centuries for upholstery, roofing and insulation. It does not rot, does not mould and is resistant to vermin due to its high silicate content. The dried seaweed is used without any other additives. The long seaweed fibres have a pleasant paper-like appearance in their feel and can be stuffed by

[19] Ökobaudat (ed.): Prozess-Datensatz: Flachsvlies (en) en de. URL: https://oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=af13e5a8-0961-454a-ad3a-7093a37fc802&version=20.19.120&stock=OBD_2021_II&lang=de. AND Process dataset: Hemp fleece (en) en de. URL: https://oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=5ef0c519-f5b2-4d45-809d-5f417f90e90b&version=20.19.120&stock=OBD_2021_II&lang=de [Accessed: 01.06.2023]

[20] Fachagentur Nachwachsende Rohstoffe e. V., FNR (Agency for Renewable Resources)(ed.): Marktübersicht. Dämmstoffe aus nachwachsenden Rohstoffen. 10 revised edition (2019), Gülzow-Prüzen

[21] Wolfgang Linden, Iris Marquardt (eds.): Ökologisches Baustofflexikon (Ecological Building Material Lexicon), Ökologisches Baustofflexikon. Bauprodukte, Chemikalien, Schadstoffe, Ökologie, Innenraum. 4th completely revised and expanded edition (2018). Berlin, Offenbach: VDE Verlag GmbH. Page318

[22] Fachagentur Nachwachsende Rohstoffe e. V., FNR (Agency for Renewable Resources)(ed.): Marktübersicht. Dämmstoffe aus nachwachsenden Rohstoffen. 10 revised edition (2019), Gülzow-Prüzen

hand. The thermal conductivity is0.043 to 0.045 W/(mK). The insulation material has building material class B2.[23]

Neptune grass (Posidonia oceanica) can also be used to make insulation material. Plant remains are used here, which are formed into spheres by the movement of the waves after they die. These balls can be found on beaches throughout the Mediterranean, where they are removed and disposed of at great expense.

An architect from Karlsruhe carried out initial tests with these balls a few years ago. He was particularly struck by the very good fire behaviour. Today, the balls are processed into stuffing wool and sold as insulation material. Although the raw material is transported from the Mediterranean region to Germany, very little energy is needed for the entire further processing. In a simple mechanical process, the fibres are prepared and the sand is sieved out. No additives are necessary. The material is naturally mould-resistant and normally flammable (building material class B2). It is not attractive to vermin and has a thermal conductivity of 0.039 to 0.046 W/(mK).

These two positive examples show that it is entirely possible to use natural resources that are 100 %natural for building insulation. In the case of the previously described insulation materials made of wood, cellulose, flax, hemp or jute, synthetic fibres are currently too often added for stabilisation or borates as flame retardants. However, there are corresponding biological and sustainable alternatives that manufacturing companies should focus on in the future. because this is the only way to produce sustainable building materials that can be recycled or composted again and again for a closed-loop system as we need it.

#### 2.1.2 Insulation materials from petroleum-based or mineral raw materials

Extruded polystyrene foam boards (short: XPS insulation boards) consist of polystyrene, a petroleum-based plastic. They have a thermal conductivity of 0.035 to 0.040 W/(mK) and building material class B1, flame retardant. XPS insulation boards are resistant to moisture and do not rot. The insulation material is repeatedly criticised because of the flame retardants and blowing agents used. Some of the blowing agents are extracted during production, some remain in the insulation material and are released into the ambient air over years when installed.

In addition, flame retardants and other synthetic additives are used.[24] The flame retardant Hexabromocyclododecane (HBCD) is no longer approved. However, it was used for many years and is therefore still found in large quantities in existing buildings. Until 2017, corresponding products were allowed to be installed in Germany, although the toxic effect was already proven in 2008 and the substance was classified by the EU as being of extreme concern.[25] The substance, which is difficult to break down, has already been found in breast milk, fish, marine mammals and birds of prey in Arctic regions.[26] Furthermore, the dismantling and especially the disposal of thermal insulation systems made of XPS containing HBCD is complex and associated with high costs, as the ingredients of concern may only be disposed of in special incineration plants.[27] In the meantime, for example, brominated polymer is used as a flame retardant, which is non-toxic and non-bio-accumulative. In addition, however, a TBBPA derivative (Tetrabromobisphenol A) is also used, the effect of which is currently being investigated by an EU programme. Like HBCD, it is also

[23] Wolfgang Linden, Iris Marquardt (eds.): Ökologisches Baustofflexikon (Ecological Building Material Lexicon), Ökologisches Baustofflexikon. Bauprodukte, Chemikalien, Schadstoffe, Ökologie, Innenraum. 4th completely revised and expanded edition (2018). Berlin, Offenbach: VDE Verlag GmbH. Page 552

[24] Wolfgang Linden, Iris Marquardt (eds.): Ökologisches Baustofflexikon (Ecological Building Material Lexicon), Ökologisches Baustofflexikon. Bauprodukte, Chemikalien, Schadstoffe, Ökologie, Innenraum. 4th completely revised and expanded edition (2018). Berlin, Offenbach: VDE Verlag GmbH. Page 638

[25] Umweltbundesamt, UBA (Federal Environment Agency) (ed.): Wie werden HBCD-haltige Dämmstoffe abfallrechtlich eingestuft? (2022) URL: https://www.umweltbundesamt.de/service/uba-fragen/wiewerden-hbcd- haltige-daemmstoffe-abfallrechtlich [Accessed: 26.03.2023]

[26] Umweltbundesamt, UBA (Federal Environment Agency): Welche negative Eigenschaften hat HBCD für Umwelt und Gesundheit? (2016) URL: https://www.umweltbundesamt.de/service/uba-fragen/welche-negativenproperties-has-hbcd-for-environment [Accessed: 26.03.2023]

[27] Interessengemeinschaft Thermischer Abfallbehandlungsanlagen in Deutschland e.V. (ITAD): Entsorgung von HBCD-haltigem Polystyrol (Styropor). Düsseldorf, Deutschland: ITAD, 2016. URL: https://www.sabprofil.de/assets/user/Duits/HBCD_document.pdf [Accessed: 26.03.2023]

said to be bio-accumulative, persistent and hormonally active in vitro.[28] There are numerous other variants of flame retardants and blowing agents that are used in XPS insulation materials and whose effects cannot be described here in individual cases. However, we have learned from the past that substances once considered unproblematic later turned out to be problematic in terms of environmental and health aspects, for example the CFC-12 blowing agent that was used in the past.

According to Ökobaudat, the total non-renewable primary energy demand (PENRT) in the production (module A1-A3) of XPS insulation materials is 2839 MJ per m³.[29] This is a very high energy demand that cannot be justified, considering the mass use of XPS in building insulation and numerous other applications, for example in the packaging industry. For PU insulation boards made of slab stock foam, the total non-renewable primary energy demand (PENRT) in production (module A1-A3) of 325 MJ per m² is given in the Ökobaudat dataset.[30] Using the layer thickness of 0.12 m given in the data set, this value can be converted to P 2708, 3 MJ per m³.

PU insulation boards made of slab stock foam or polyurethane rigid foam boards are petroleum-based rot proof products that are created in a chemical reaction, with the help of the blowing agent pentane. HCFC-141b was also used as a blowing agent, but has been banned in Germany since 2004. Furthermore, the Ecological Building Material Lexicon (Ökologisches Baustofflexikon) lists many other formerly and currently used blowing agents, flame retardants and additives, some of which have been banned over time and then replaced by alternatives. Polyurethane rigid foam panels are considered harmless to health when installed, but during production employees come into contact with numerous toxic substances. Subsequent outgassing of the blowing agents can also be assumed. In addition, the plastic may only be disposed of in small quantities and is therefore incinerated, producing toxic hydrochloric acid. The insulation value of rigid Polyurethane foam boards with a thermal conductivity of 0.025 to 0.030 W/(mK) is particularly good. In addition, depending on the product, building material class B2 (normal flammability) or B1(low flammability) is possible.

Fig. 7: Installation of PU rigid foam panels as above-rafter insulation. Source: Baustoffwissen, RM Handelsmedien GmbH & Co. KG: Dämmstoffe, Einsatzbereiche von PU-Hartschaum. URL: https://www.baustoffwissen.de/baustoffe/baustoffknowhow/daemmstoffe/pu-hartschaum-polyurethan-daemmstoff-platten-einsatzbereiche-dach-boden-wand-wdvs-brandriegel-sandwich-elemente/ [Accessed: 14.06.2023]

The possible building material class B1of XPS insulation boards or rigid Polyurethane foam boards is certainly an advantage. However, if a fire does occur, the fire behaviour is very dangerous. Rigid

[28] Christian Sinn, Christoph Semisch, Michael Braungart, Peter Mösle: Flammschutzmittel für ein effektives Recycling von expandiertem Polystyrol (EPS). URL: https://muellundabfall.de/ce/flammschutzmittel-fuer-ein-effektives-recycling-von-expandiertem-polystyrol-eps/detail.html [Accessed: 31.05.2023]

[29] Ökobaudat (ed.): Prozess-Datensatz: XPS-Dämmstoff (en) en de. URL: https://oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=43e99b8c-90d8-4fcd-90ce-342fb0b7366e&version=20.19.120&stock=OBD_2021_II&lang=de [Accessed: 01.06.2023]

[30] Ökobaudat (Hrsg.): Prozess-Datensatz: PU-Dämmplatten aus Blockschaumstoff (de) ende. URL: https://oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=880e05ea-55c6-4346-a3ea-5af0e5f299e2&version=00.09.000&stock=OBD_2021_II&lang=de [Accessed: 14.06.2023]

Polyurethane foam boards burn with a strong formation of smoke, which makes orientation and escape in the burning building difficult and can lead to health damage. XPS insulation boards are suspected of emitting toxic gases in case of fire. The question arises as to what risks we should accept for a good insulation value. The Ecological Building Material Lexicon (Ökologisches Baustofflexikon) points out that these insulation materials should only be used from an ecological point of view if their efficiency (very good insulation value, thus thin component layer) is absolutely necessary and no other insulation material can be used accordingly.[31]

As an example of the mineral insulation materials, the most important aspects of rock wool are explained below. Its thermal conductivity is 0.035 to 0.040 W/(mK). Rock wool is considered non-combustible with building material class A1. It consists of artificially produced mineral fibres based on sedimentary or magmatic rocks. Binding and water-repellent agents are added as additives.

A mixture of the rock, coke, recycled wool and lime is prepared for the melting process. Binding and impregnating agents are used when the threads are pulled out of the molten mass. The binder polymerises in the curing oven. The fibres of rock wool can cause irritation of the respiratory tract, itching and reddening of the skin if they come into contact with it. Mineral wool fibres were classified as suspected carcinogens in the 1980s. The so-called WHO fibres, dust fibres of a certain size and geometry, are respirable and therefore banned.[32] Products available on the market today no longer contain respirable fibres. In terms of non-renewable primary energy demand (PENRT) in production (module A1-A3), rock wool with a value of 1137MJ per m³[33] is better than XPS insulation (2839 MJ per m³) and wood fibre insulation board from the wet process (1823 MJ per m³).

The recycling of clean used rock wool is possible, but the take-back options by manufacturers are still in their infancy and are only offered sporadically, especially for the commercial sector. The lamination of rock wool with paper, aluminium or plastic film further complicates or prevents recycling. This example again clearly shows how important it is to use pure building materials that can be reused or recycled accordingly.

With regard to the total non-renewable primary energy demand (PENRT) in production (modules A1-A3), the values of bio-based insulation materials are mostly in the lower range, provided that the processing intensity is relatively low or if residual materials were recycled anyway, as in the case of jute or seaweed, for example. Overall, it can be said that little-processed bio-based insulation materials or recycled insulation materials have the best values here and the energy requirement is amortised in less than one year.[34] Insulation materials from renewable raw materials also offer the advantage that the raw materials store $CO_2$ during the growth phase, i.e. during the production of the insulation resource, while $CO_2$ is already released during the production of the basic materials for the synthetic insulation materials.

## 2.2 Building physical properties and material health of insulation materials

The data on thermal conductivity in W/(mK) differ slightly in the third digit after the decimal point. This minimal distinction is due to the production by different manufacturers. According to Table 1, the values in the preceding text from the Ecological Building Material Lexicon (Ökologisches Baustofflexikon) are in part minimal worse in terms of insulation value than the data from the Agency for Renewable Resources (Fachagentur Nachwachsende Rohstoffe e. V., FNR). In summary, it can be said that the values of petroleum-based and mineral-based insulation materials turn out to be somewhat more advantageous than the values of biological insulation materials.

[31] Wolfgang Linden, Iris Marquardt (eds.): Ökologisches Baustofflexikon (Ecological Building Material Lexicon), Ökologisches Baustofflexikon. Bauprodukte, Chemikalien, Schadstoffe, Ökologie, Innenraum. 4th completely revised and expanded edition (2018). Berlin, Offenbach: VDE Verlag GmbH. Page 485

[32] ibid., p. 571.

[33] Ökobaudat (Hrsg.): Prozess-Datensatz: ROCKWOOL Steinwolle-Dämmstoff im mittleren Rohdichtebereich (de) ende. URL: https://oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=eca9691f-06d7-48a7-94a9-ea808e2d67e8&version=00.07.000&stock=OBD_2021_II&lang=de[Accessed: 14.06.2023]

[34] Db deutsche bauzeitung: Dunkelziffer graue Energie? Primärenergiegehalte von Dämmstoffen. URL: https://www.db-bauzeitung.de/wissen/energie/dunkelziffer-graue-energie/ [Accessed: 11.06.2023]

| Insulating material | Thermal conductivity W/(m·K) Rated value λ | Bulk density ρ kg/m³ | Water vapour diffusion resistance μ | Heat capacity c J/kg·K | Building material class according to DIN 4102-1 | Fire behaviour according to DIN EN13501-1 |
|---|---|---|---|---|---|---|
| Flat mats | 0,039 | 30–40 | 1–2 | 1.550–2.300 | B2 | E |
| Hemp (stuffing wool) | 0,045 | 50–60 | 1–2 | 2.200 | B2–B1 | E, C-s2, d0 |
| Hemp jute | 0,043 | 35–40 | 1–2 | 2.300 | B2 | E |
| Hemp mats | 0,043 | 30–110 | 1–2 | 1.600–2.300 | B2 | E |
| Wood fibre (loose) | 0,040 | 30–45 | 1–2 | 2.100 | B2 | E |
| Wood fibre mats | 0,038 | 40–55 | 1–3 | 2.100 | B2 | E |
| Fibreboard | 0,040 | 110–270 | 2–5 | 2.100 | B2 | E |
| Wood chips | 0,045 | 90–360 | 2 | k. A. | B2 | E |
| Wood wool panels | 0,090 | 330–500 | 2–5 | 2.100 | B1 | B, s1, d0 |
| Jute mats | 0,039 | 30–40 | 1–2 | 2.350 | B2 | E |
| Corkboard (exp.) | 0,040 | 120 | 5–10 | 1.800 | B2 | E |
| Cork clay board | 0,080 | 200–300 | 10 | 1.254 | B2–B1 | E |
| Sheep's wool | 0,036 | 20–90 | 1–2 | 1.300–1.730 | B2 | E |
| Reed panels | 0,065 | 150 | 3–6,5 | 1.200 | B2 | E |
| Seaweed | 0,045 | 65–75 | 1–2 | 2.502 | B2 | E |
| Straw bale | 0,052 | 85–115 | 2 | 2.000 | B2 | E |
| Straw blow-in insulation | 0,043 | 105 | 2,8 | 2.100 | B2 | E |
| Cellulose flakes | 0,039 | 28–65 | 1–2 | 2.100–2.544 | B2 | E bis B-s2, d0 |
| Cellulose boards | 0,042 | 70–145 | 2–3 | 2.000 | B2 | E |
| Polystyrene (exp.) | 0,035 | 11–30 | 20–100 | 1.400 | B2–B1 | E |
| Rock wool panels | 0,035 | 15–130 | 1–2 | 830–1.000 | A1 | A1 |

Table 1: Overview of the most important technical values for insulation materials. Source: Fachagentur Nachwachsende Rohstoffe e. V., FNR (Agency for Renewable Resources): Marktübersicht. Dämmstoffe aus nachwachsenden Rohstoffen. 10 überarbeitete Auflage (2019), Gülzow-Prüzen. Table translated by Sandra Böhm.

The bio-based insulation materials can score points with regard to other building physics properties. Materials with a low water vapour diffusion resistance factor are able to transport moisture that has penetrated the material and allow it to dry out again elsewhere. The mostly different sized pores in natural insulation materials lead to the fact that the moisture first migrates through the small pores while the effectiveness of the larger pores for the insulating effect is maintained. In an insulation material with uniform pore size, this effect does not occur. In Table 1,the very low water vapour diffusion resistance values of most bio-based insulation materials are striking compared to the values of extruded polystyrene. This absorption behaviour of biological insulation materials has a regulating effect on the humidity level of indoor spaces and is particularly advantageous for a pleasant indoor climate in today's increasingly airtight residential buildings.[35]

The specific heat capacity refers to the thermal protection in summer. Materials with high values offer better thermal protection here, as they pass on incident heat only very slowly. In the summer heat, the high heat storage capacity of natural insulation materials means that the absorbed heat is only released with a long delay, i.e. during the night, and not in the afternoon, as is the case with synthetic insulation materials, for example.[36]

Such beneficial properties of natural insulation materials have already been proven in studies. In contrast to mineral and synthetic insulating materials, natural insulating materials can compensate moisture fluctuations to a certain extent and thus have a positive influence on the indoor climate, which is particularly beneficial for allergy sufferers. The fire behaviour should also be mentioned again. The bio-based insulation materials burn rather slowly and only a small amount of smoke is produced. As long as no chemical components have been added, it can also be assumed that no toxic smoke gases are produced. Rigid foams, on the other hand, melt, drip burning and burn very quickly overall; this is accompanied by strong, dark smoke formation.[37]

For special applications, insulation materials such as XPS or PUR insulation materials are still justifiable to a certain extent, for example, in areas exposed to moisture, e.g. as perimeter or base insulation, inverted roof and terrace insulation. It is always necessary to weigh up which insulation material is best suited to which application in order to use the appropriate products in a targeted manner and to reduce building materials from finite resources as much as possible. The goal should therefore be to establish pure insulation materials from renewable raw materials (NawaRo) on the market and to use them on a broad scale. However, this will

[35] Fachagentur Nachwachsende Rohstoffe e. V., FNR (Agency for Renewable Resources) (ed.): Marktübersicht. Dämmstoffe aus nachwachsenden Rohstoffen. 10 revised edition (2019), Gülzow-Prüzen

[36] ibid.

[37] Fachagentur Nachwachsende Rohstoffe e. V., FNR (Agency for Renewable Resources): Aktuelle Nachricht: Weg frei für mehr Natur-Dämmstoffe beim Bauen. (2020) URL: https://www.fnr.de/presse/pressemitteilungen/aktuelle-mitteilungen/aktuelle-nachricht/weg-frei-fuer-mehr-natur-daemmstoffe-beim-bauen [Accessed: 25.05.2023]

only work if we use these raw materials efficiently, for example the residues and by-products from already existing material flows, and exclusively in a closed-loop system.

Looking at the material health of 100 % biological insulation materials, it becomes clear that their use in living spaces could be of outstanding importance especially for vulnerable population groups. In the future, the need for housing and care facilities for the elderly and those in need of care, as well as childcare facilities in our communities, will increase. In planning these facilities, material health will play a huge role in improving the quality of life and well-being of these target groups, rather than compromising them. Natural building materials, including biological insulation materials, which positively influence the indoor climate and do not emit pollutants, will be increasingly in demand.

The people who work in the production of insulation materials should not be ignored. Particularly in the production of synthetic insulation materials, there is a great potential for health hazards that must be minimised as far as possible through appropriate alternatives.

## 3 CONCLUSION

The petroleum-based insulation materials, e.g. XPS insulation boards, or the mineral insulation materials, e.g. rock wool, undoubtedly have very good technical properties and a high insulation value. However, if one considers ecological and health-relevant aspects, they are no longer convincing. If one looks at the long lists of ingredients of synthetic and mineral insulation materials, they are not an alternative from an ecological point of view. Crude oil as the raw material basis for synthetic plastics can possibly only be used for a few more decades. According to Wecobis, coal is an alternative base material, also a non-renewable raw material, the processing of which would require even more energy – from an ecological point of view and, with a view to our descendants, also from a social point of view, thus not an alternative either.[38] Some of the numerous additives are considered worrying or even toxic. This also makes disposal time-consuming and expensive, recycling difficult or impossible – depending on the condition of the used insulation materials. Land filling is usually no longer permitted because toxic substances are contained and landfill space is running out. In addition, toxic substances are produced when some synthetic insulation materials are burnt. We must realise that we owe it to future generations not to produce more hazardous waste that will sooner or later end up in the environment.

The renewable raw material base of NawaRo insulation materials speaks for itself. Of course, biological insulation materials are not free of concerns. Here, too, additives are mixed in that could either have health effects (borates) or interfere with recycling or composting (bicomponent support fibres). However, these additives are used to a much lesser extent. In addition, alternative flame retardants and biological support fibres are already available. With insulation materials made from seaweed, there are even products that manage entirely without additives. Insulation materials made from renewable raw materials are usually easier to reuse or recycle at the end of their life cycle and can be thermally recycled without any problems. Ideally, they are even compostable.

Insulation materials made from renewable raw materials are convincing overall because of their contribution to healthier living spaces, if they are installed on the inside of the room - for example, in the case of retrofitted insulation in an existing building. Due to their natural properties, they contribute to moisture regulation in this case. In addition, they have a higher thermal capacity than mineral or synthetic insulation materials and are therefore particularly advantageous in terms of heat protection. Even if the insulation values are sometimes somewhat lower than those of mineral wool and co., they are still convincing due to their overall balance with regard to their renewability, $CO_2$ storage during growth and the advantageous properties with regard to heat protection, room climate regulating properties and easily assessable fire behaviour.

The sourcing of raw materials plays a major role in ecological considerations. Of course, it makes no sense to transport coconut fibres halfway round the world to insulate our houses with them, but there are exceptions such as seaweed from the Mediterranean region and many domestic alternatives. The seaweed insulation materials, jute insulation mats or cellulose insulation materials also require relatively little

[38] Wecobis (Hrsg.): Polyurethan-Hartschaum (PUR/PIR), Lebenszyklus, Rohstoffe, Verfügbarkeit. URL: https://www.wecobis.de/bauproduktgruppen/daemmstoffe/aus-synthetischen-rohstoffen/polyurethan-hartschaum.html [Accessed: 07.06.2023]

manufacturing energy. However, softwood fibreboards from the wet process, for example, are an exception, because a lot of energy is used for their drying process. Such production processes worsen the ecological balance and counteract $CO_2$ storage during plant growth.

The demand for insulation materials will rise sharply in the near future due to climate change and the new directives and laws. All in all, it will be worthwhile in the future to use insulating materials made from renewable resources that are 100% biological if possible. Only in this way will we be able to combat the already existing scarcity of resources. The use of renewable raw materials and in particular the full use of biological residues and by-products will conserve the non-renewable or only very slowly renewable raw material sources of our earth.

In order to meet the responsibility of the building sector towards climate, environmental and nature protection, it is necessary to establish a sustainable resource management in the building sector (Nature-Based Solutions, NBS) in order to coordinate the material flows better. In this context, the availability of renewable raw materials must be recorded and monitored across all sectors. This is an important basis for the development of new alternative building materials and thus also for the development of sustainable biological insulation materials. After all, what use are new products if their production has to be stopped again due to a shortage of raw materials?

In building practice, sustainable resource management would lead to building materials being used efficiently and individually adapted to their application. Building materials from renewable raw materials produced according to certain ecological, economic and social criteria should always have priority. Building materials from finite resources should only be used in exceptional cases. The guidelines for such sustainable resource management would be based on the principles of recyclability, renewability, health and environmental compatibility and, of course, the necessary technical properties.

Numerous research projects continue to work on the development of new, efficient insulation materials from renewable raw materials. For example, a team of researchers from Osnabrück and Hamburg is developing an aerogel insulating material made of lignin, which is a residual material from paper production. Aerogels consist almost entirely of air, i.e. of very many microscopically small pores, which is why heat is conducted extremely poorly in them. The size of the pores in the nano-meter range is the decisive factor in comparison with other insulation materials such as Styrofoam, whose pores are around 200 micrometres in size.[39] Aerogels have been around for a long time and are used in the aerospace industry, for example. Until now, however, they were mostly made of plastics or silicates. Mark Fricke, who was also involved in the development of the “conventional” aerogels, has now developed the innovation from renewable raw materials with his team. Mark Fricke considers the potential of the new insulation material to be particularly high. Large quantities of lignin are available as residual material and due to the particularly good insulating value, the insulating material can be installed in a material-saving and thus very versatile way. The team is currently still working on market readiness.[40]

This example shows that it is possible to produce bio-based and sustainable insulation materials that have no limitations in terms of technical properties compared to petroleum-based insulation materials. Currently, the great potential of bio-based insulation materials is that they are renewable, often produced with low energy consumption, and that biogenic residues are used as a resource within a biological cycle-based system - i.e. without the use of synthetic additives or substances that are harmful to the environment and health. In the future, it is essential that all information about all additives and substances used in production be disclosed. Such full declarations are a prerequisite for the use of building materials in a cycle-based system.

The advantages of biological insulating materials with regard to their physical properties, in particular summer heat insulation and the regulating properties on the indoor climate, as well as the assessable properties in case of fire, were made clear in this paper. It aimed to show that the origin of the raw materials, the production, the properties during use and disposal of biological insulation materials are advantageous for environmental protection, the fight against climate change, the conservation of resources and the creation of healthy living spaces.

[39] Wille, Joachim auf Klimareporter: Der neue Super-Dämmstoff. URL: https://www.klimareporter.de/gebaeude/der-neue-super-daemmstoff (2023) [Accessed: 13.05.2023]
[40] ibid.

## 4 REFERENCES


Bundesministerium für Ernährung und Landwirtschaft (Federal Ministry of Food and Agriculture): Akzeptanz von Baumaterialen aus nachwachsenden Rohstoffen. 2018. URL: https://www.waldkulturerbe.de/aktuelles/aktuelles/akzeptanz-von-baumaterialen-aus-nachwachsenden-rohstoffen

Bundesinformationszentrum Landwirtschaft: Welches Potenzial hat Hanf als Nutzpflanze? (2022) URL: https://www.landwirtschaft.de/landwirtschaft-verstehen/wie-arbeiten-foerster-und-pflanzenbauer/welches-potenzial-hat-hanf-als-nutzpflanze

Db deutsche bauzeitung: Dunkelziffer graue Energie? Primärenergiegehalte von Dämmstoffen. URL: https://www.db-bauzeitung.de/wissen/energie/dunkelziffer-graue-energie/

Fachagentur Nachwachsende Rohstoffe e. V., FNR (Agency for Renewable Resources): Aktuelle Nachricht: Weg frei für mehr Natur-Dämmstoffe beim Bauen. (2020) URL: https://www.fnr.de/presse/pressemitteilungen/aktuelle-mitteilungen/aktuelle-nachricht/weg-frei-fuer-mehr-natur-daemmstoffe-beim-bauen

Fachagentur Nachwachsende Rohstoffe e. V., FNR (Agency for Renewable Resources): Marktanteil von NawaRo-Dämmstoffen wächst, Umfrage zum Einsatz biobasierter Baustoffe (2021). URL: https://www.fnr.de/presse/pressemitteilungen/aktuelle-mitteilungen/aktuelle-nachricht/marktanteil-von-nawaro-daemmstoffen-waechst

Hochschule Pforzheim (Pforzheim University): From the Attitude-Behaviour-Gap to the Producer-People-Gap. 2018. URL: https://www.hs- pforzheim.de/news_detailview/news/vom_attitude_behaviour_gap_to_the_producer_people_gap_1

Interessengemeinschaft Thermischer Abfallbehandlungsanlagen in Deutschland e.V. (ITAD): Entsorgung von HBCD-haltigem Polystyrol (Styropor). Düsseldorf, Deutschland: ITAD, 2016. URL: https://www.sabprofil.de/assets/user/Duits/HBCD_document.pdf

International Union for Conservation of Nature (IUCN): About Nature-based Solutions. URL: https://www.iucn.org/our-work/nature-based-solutions

Ökobaudat: Prozess-Datensätze:

Flachsvlies (en) en de. URL: https://oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=af13e5a8-0961-454a-ad3a-7093a37fc802&version=20.19.120&stock=OBD_2021_II&lang=de

Hanfvlies (en) en de. URL: https://oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=5ef0c519-f5b2-4d45-809d-5f417f90e90b&version=20.19.120&stock=OBD_2021_II&lang=de

Holzfaserdämmplatte (Nassverfahren) (de) ende. URL: https://oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=393f494d-8738-4330-aa5e-1652bb29b574&version=20.19.120&stock=OBD_2021_II&lang=de

PU-Dämmplatten aus Blockschaumstoff (de) ende. URL: https://oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=880e05ea-55c6-4346-a3ea-5af0e5f299e2&version=00.09.000&stock=OBD_2021_II&lang=de

ROCKWOOL Steinwolle-Dämmstoff im mittleren Rohdichtebereich (de) ende. URL: https://oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=eca9691f-06d7-48a7-94a9-ea808e2d67e8&version=00.07.000&stock=OBD_2021_II&lang=de

XPS-Dämmstoff (en) en de. URL: https://oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=43e99b8c-90d8-4fcd-90ce-342fb0b7366e&version=20.19.120&stock=OBD_2021_II&lang=de

Zellulosefaser Einblas-Dämmstoff (en) en de. URL: https://oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=c355d75b-9026-4899- a41c-e5d221c424f2&version=20.19.120&stock=OBD_2021_II&lang=de

Christian Sinn, Christoph Semisch, Michael Braungart, Peter Mösle: Flammschutzmittel für ein effektives Recycling von expandiertem Polystyrol (EPS). URL: https://muellundabfall.de/ce/flammschutzmittel-fuer-ein-effektives-recycling-von-expandiertem-polystyrol-eps/detail.html

Umweltbundesamt, UBA (Federal Environment Agency): Energiesparende Gebäude (2022). URL: https://www.umweltbundesamt.de/themen/klima-energie/energiesparen/energiesparende-gebaeude#gebaude-important-for-climate-protection

Umweltbundesamt, UBA (Federal Environment Agency)(ed.): Klimaneutraler Gebäudebestand 2050. Energieeffizienzpotentiale und die Auswirkungen des Klimawandels auf den Gebäudebestand. Dessau- Roßlau, November 2017. URL:https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2017-11-06_climate-change_26-2017_klimaneutraler- gebaeudebestand-ii.pdf

Umweltbundesamt, UBA (Federal Environment Agency) (ed.): Wie werden HBCD-haltige Dämmstoffe abfallrechtlich eingestuft? (2022) URL: https://www.umweltbundesamt.de/service/uba-fragen/wiewerden-hbcd- haltige-daemmstoffe-abfallrechtlich

Umweltbundesamt, UBA (Federal Environment Agency): Welche negative Eigenschaften hat HBCD für Umwelt und Gesundheit? (2016) URL: https://www.umweltbundesamt.de/service/uba-fragen/welche-negativenproperties-has-hbcd-for-environment

Verband Holzfaserdämmstoffe (ed.): Informationsdienst Holz: Holzfaserdämmstoffe. Revised 3rd edition, 2018, Wuppertal

WECOBIS Ökologisches Baustoffinformationssystem (Ecological Building Materials Information System): Borate, Überblick. URL: https://www.wecobis.de/service/sonderthemen-info/svhc-fsm-info/svhc-borate-info.html

Wecobis (Hrsg.): Polyurethan-Hartschaum (PUR/PIR), Lebenszyklus, Rohstoffe, Verfügbarkeit. URL: https://www.wecobis.de/bauproduktgruppen/daemmstoffe/aus-synthetischen-rohstoffen/polyurethan-hartschaum.html

Wille, Joachim auf Klimareporter: Der neue Super-Dämmstoff. URL: https://www.klimareporter.de/gebaeude/der-neue-super-daemmstoff (2023)