CLIMATE AND POLLUTION AGENCY

Chemicals in products

Alternatives to the use of flame retarded EPS in buildings

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Prepared by

COWI

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Preface

Hexabromocyclododecane (HBCD) was nominated for inclusion in the Stockholm Convention on Persistent Organic Pollutants by Norway in 2008.

The Persistent Organic Pollutants Review Committee, a subsidiary body to the Stockholm Convention, has considered the information provided and concluded that HBCD, due to its adverse effects, persistence, bioaccumulation and long-range transport, should proceed to the risk management phase. The POPs Review Committee has set up an intersessional working group to prepare a draft risk management evaluation to evaluate socio-economic implications of possible control measures for the chemical.

HBCD is a flame retardant used mainly in expanded and extruded polystyrene (EPS/XPS). The flame retarded polystyrene is mainly used as insulation materials for the building and construction sector. In order to inform the evaluations prepared by the POPS Review Committee, Norway has initiated a study of the alternatives to the use of HBCD in building insulation materials. Possible alternative flame retardants for use in HBCD have recently been evaluated elsewhere, and the current study focuses of alternative insulation materials to flame retarded polystyrene. In order to limit the extent of the study, Norway has decided to focus the study on alternatives to flame retarded EPS.

The Norwegian Climate and Pollution Agency (Klif) has engaged the consulting company COWI A/S Denmark to undertake the study. The project has been followed by a steering group consisting of Liselott Säll and Christina Charlotte Tolfsen, Klif.

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1. Executive summary

HBCD is a flame retardant used mainly in expanded and extruded polystyrene (EPS/XPS). The flame retarded polystyrene is mainly used as insulation materials for the building and construction sector.

The current study evaluates selected alternatives to flame retarded EPS used in the building sector. The selected materials are stone wool, polyurethane foams (PUR/PIR), wood fibre boards and cellular glass. The materials are evaluated as to their technical properties, fire safety performance, environmental and health profile, and price.

Flame retarded EPS is used for a wide range of applications and the study has evaluated more closely a number of key applications: In external façade insulation, flat roof insulation, floor insulation and sandwich panels. For a key application area of EPS (and XPS), insulation directly against the ground, alternatives have not been evaluated, because non-flame retarded grades could in general be used for these applications.

For all the concerned application areas alternative insulation materials are marketed. If the use of flame retarded EPS is restricted, the flame retarded EPS would likely be replaced by several other insulation materials depending on the specific application areas. The price of the cheapest alternatives ranges from more or less the same price as for flame retarded EPS to approximately 30% more. Alternatives of significantly higher price exist, but these are typically used because they have some desired technical advantages and would probably not be the first choice substitutes for general application.

The alternatives have different advantages and disadvantages as compared with the EPS. Most of the alternatives have better performance with regard to fire safety than the flame retarded EPS, and a change from flame retarded EPS to the alternatives would not compromise fire safety.

The most marked disadvantage of the flame retarded EPS as compared to alternatives is the presence of HBCD, which is considered a PBT and POP substance. Although some PUR/PIR materials may include halogenated flame retardants of some concern, none of the substances are identified as PBT or POP substances. Besides the impacts of the emissions of HBCD from different life cycle phases, the presence of HBCD in the EPS hampers the post consumer recycling of the EPS insulation materials.

Apart from this, the flame retarded EPS scores well in the comparison with the other materials (provided that the fire performance is acceptable), in particular if the EPS by the final disposal is disposed of for incineration with energy recovery. None of the evaluated alternatives have an outstanding environmental profile, indicating significant environmental advantages compared to EPS without HBCD. Within each group of insulation material there is a potential for improving the environmental profile and the comparison between materials is very sensitive to the profile of the specific products compared. Evaluation of possible alternative flame retardants for use in HBCD have been beyond the scope of the current study, but the introduction of more environmentally friendly flame retardants than HBCD, may lead to EPS with an environmental profile matching other insulation materials.

For some applications, flame retarded EPS may be replaced by grades without flame retardants, by use of thermal barriers and fire-resistive construction principles. In some countries building regulation stipulates the use of flame retarded grades for all applications, whereas in others, the performance of the entire building element is tested. In the latter countries, EPS without flame retardants are used for e.g. floor and flat roof insulation using constructions where the EPS is covered with non-combustible materials with high thermal heat capacity, e.g. concrete. The costs of introducing thermal barriers have not been assessed, but the fact that this solution is widely used in some countries indicates that the costs for some applications would not be higher than the cost of changing to alternative flame retarded materials.

2. Abbreviations and acronyms

CMR	Carcinogenic, mutagenic or toxic to reproduction
EC	European Community
EFTA	European Free Trade Association
EU	European Union
EPD	Environmental Product Declaration
EPS	Expanded polystyrene
EUMEPS	European Manufacturers of Expanded Polystyrene
ETICS	External thermal insulation composite systems
FU	Functional unit (used in a LCA)
HBCD	Hexabromocyclododecane (also abbreviated HBCDD)
LCA	Life cycle assessment
OECD	Organisation for Economic Cooperation and Development
PBT	Persistent, bioaccumulative and toxic
PIR	Polyisocyanorate
POP	Persistent organic pollutant
PUR	Polyurethane
SIDS	Screening Information Dataset
TBBPA	Tetrabromobisphenol a
TCCP	Tris-(2-chloroisopropyl)-phosphate (also abbreviated TMCP)
TEP	Triethyl phosphate
VOC	Volatile organic carbon
UK	United Kingdom
USA	United States of America
XPS	Extruded polystyrene

3. Application of HBCD in building insulation materials

The following chapter provides a short description of the application of EPS, flame retarded with HBCD, in the building sector. The description focuses mainly on the advantages of the EPS for different applications in order to identify the properties which have to be matched by alternative insulation materials. In the subsequent chapters, where the flame retarded EPS is compared with potential alternative materials, both advantages and disadvantages of the materials are assessed.

3.1 Use of HBCD in insulation materials

The main use of hexabromocyclododecane (HBCD) is as flame retardant in insulation foam boards of expanded polystyrene (EPS) and extruded polystyrene (XPS) which are widely used by the construction sector.

Although at least one other brominated flame retardants is marketed for use in EPS/XPS, in practice HBCD is the flame retardants of choice in these materials. Globally, approximately 23,000 tons HBCD is used annually; the majority for production of flame retarded EPS/XPS (UNEP, 2011).

Compared to solid polystyrene which is processed at temperatures up to 260°C, the manufacture of foam polystyrene with physical blowing agents is carried out at approximately 120°C for bead foam and about 200°C for extruded foam. These lower temperatures enable the less thermally stable cycloaliphatic bromine compounds such as HBCD to be used. They very well fit with the degradation range of the polystyrene matrix of the foam and can be used in fairly small amounts as reported in a recent note by Troitsch for the European HBCD Industry Working Group (Troitzsch, 2008).

EPS boards contain typically 0.5% HBCD by weight in the final product (Morose, 2006) and the maximum concentration of HBCD in EPS beads is assumed to be 0.7 % (EU RAR, 2006). In XPS produced in Europe, HBCD is used in up to 3 % loading to meet technical and flammability foam requirements (Troitzsch, 2008). HBCD levels in XPS foams produced in Canada are typically from 0.5 to 1% (EPSMA et al., 2009 as cited by Environment Canada, 2010).

In EPS, the HBCD is often used in conjunction with dicumyl peroxide (CAS No 80-43-3) in concentrations < 0.5 % (Troitzsch, 2008). The use of dicumyl peroxide as synergist with HBCD in EPS to enhance the flame retardant activity has also been reported from Canada (Environment Canada, 2010). How widespread the use of dicumyl peroxide as synergist in the EPS is has not been further investigated in this study.

In 2007 the total world demand for EPS was 3.06 million tons (Posner, 2011). According to a recent market report the construction industry is the largest EPS market, with a worldwide share of just less than 60% and this sector‘s importance is expected to continue increasing in the future (Ceresana Research, 2010). Consequently the global EPS market for construction is about 1.8 million tons per year

According to the EU risk assessment report in Europe in 2001 some 420,000 tonnes of EPS was used for construction applications; 170 000 of this is used in Eastern Europe. In Western Europe approximately 70 % of this EPS is flame-retarded grades, in Eastern Europe more than 99 % (EU RAR, 2008).

EPS vs. XPS

EPS and XPS are both made from polystyrene, but by two different processes.

EPS is produced from solid beads of polystyrene. Expansion is achieved by virtue of small amounts of gas contained within the polystyrene bead. The gas expands when heat in the form of steam is applied, thus forming closed cells of EPS. These cells occupy approximately 40 times the volume of the original polystyrene bead. The beads are pressed together at elevated temperatures, the material itself acting as adhesive. EPS is manufactured in large blocks that are subsequently cut by hot-wire machines into virtually any special shape or sheet (Dyplast, 2010).

XPS foam begins with solid polystyrene crystals. The crystals, along with special additives and a blowing agent, are fed into an extruder. Within the extruder the mixture is combined and melted under controlled conditions of high temperature and pressure into a viscous plastic fluid. The hot, thick liquid is then forced in a continuous process through a die. As it emerges from the die it expands to a foam, is shaped, cooled, and trimmed to dimension. XPS is extruded into smaller blocks of finite dimension, which may require gluing multiple billets together to achieve the necessary size. (Dyplast, 2010). The resulting boards have almost 100% closed cells, and are strong and highly moisture resistant.

EPS and XPS are used for many of the same applications such as roof insulation, external walls insulation, cavity insulation and floor insulation. Due to higher resistance to compression and deformation and higher water resistance, the XPS is particularly suitable for applications where high mechanical and water resistance is required. Examples are external cladding, insulation below surfacing with high loads and insulation of basement walls and foundations. XPS is typically more expensive that EPS. According to the EU risk Assessment report, in the EU the major applications of XPS were for basement walls and foundations (30%), inverted roofs (18%) and cavity insulation (17%).

Considering that for the major application areas both EPS and XPS can be used, due to limits in resources the current study focus on alternatives to flame retarded EPS. Most of the alternatives are also considered relevant alternatives to XPS for the main application, although the comparison between the alternatives and polystyrene foam may be slightly different if the alternatives are compared to the XPS.

Alternative flame retardants for EPS

According to industry in Europe, currently there are no technically and commercially feasible alternatives to HBCD for EPS and XPS applications (BSEF, 2011).

A study on alternatives to the flame retardants TBBPA and HBCD listed tree possible brominated flame retardants as alternatives to HBCD in EPS and XPS: tetrabromocyclooctane, dibromo ethyl dibromocyclohexane and TBBPA bis (allyl ether) (Morose, 2006). Whereas the two first substances seem not to be produced today, TBBPA bis (allyl ether) (CAS No 25327-89-3) is still marketed as flame retardant for EPS (Chemtura, 2011a). Industry has informed that other brominated flame retardants are to some extent used in North America, but that currently only HBCD can be used in the manufacturing processed applied in Europe (Klif, 2010).

In March 2011, Dow Global Technologies LLC (USA) announced the invention and development of a new, high molecular weight brominated polymeric flame retardant (Dow, 2011). The polymeric flame retardant is according to the company expected to be the ‘next generation industry standard’ flame retardant for use in both extruded polystyrene (XPS) and expanded polystyrene (EPS) foam insulation applications globally. According to the company the new polymer ensures the same flame retardancy as HBCD while offering a superior environmental profile. The exact chemical composition has not yet been reported. It is expected that the flame retardant licensees will have interim quantities available throughout 2011. This will be followed, likely in 2012, by large plant construction by the licensees, making significantly larger commercial volumes available by 2013-2015 that are in line with the current HBCD market demand (Dow, 2011). As the first licensee of this technology, Chemtura Corporation (USA) will have the rights to manufacture and sell this novel flame retardant.

Another major global manufacturer of EPS and XPS, BASF (Germany), has announced its support to the new flame retardant, and the company plans to test new product formulations on a larger scale. Should these tests and customer trials also prove successful, BASF will then start to switch all product lines to the new flame retardant but according to the company industry-wide, several years will be needed to replace HBCD completely (BASF, 2011). The actual number of years has not been indicated.

It has been beyond the scope of the current study to evaluate chemical alternatives to HBCD in EPS and XPS, but it is noted that the most recent developments seems to be a break trough for a suitable flame retardant alternative to HBCD.

3.2 Technical properties of flame retarded EPS

EPS is produced in a variety of densities providing a varying range of properties for specific applications. A number of standards exist which define the specifications of the products and a large number of test parameters.

In Europe, the properties of EPS insulation materials for buildings and their test methods are defined in EN 13163, which is mandatory for all EU countries. The trade organisation EUMEPS has agreed on a set of standard product types in order to give transparency to the customers. The different grades have different colour codes and products containing a flame retardant are identified with the addition of a red stripe.

The product types are numbered after the properties for compressive stress at 10 % compression: EPS 30, EPS 60, EPS 70 and so on. The compressive strength is the measure of the maximum uniaxial compressive stress that the material is capable of withstanding without being crushed. The property measured in the test is the compressive stress in the unit Pascal, but both terms, compressive strength and compressive stress, are used when describing the properties of the materials.

Examples of properties by EPS type from one manufacturer is shown in Table 3.1. The compressive strength is positively correlated with the density of the EPS, as well as the moisture properties. The EPS with higher density has better moisture properties resulting in a higher water vapour diffusion resistance factor which describes how many times better a material or product is at resisting the passage of water vapour, compared with an equivalent thickness of air.

The thermal conductivity decreases slightly with increasing density which means that the more compact types with higher density also have the best insulating properties. The different grades are used for different applications as further discussed in the next section.

Table 3.1 Examples of properties by EPS type (after Jablite, 2011)

	Unit	EPS 70	EPS 100	EPS 150	EPS 200	EPS 250
Mechanical properties						
Compressive strength @ 10% compression *1	kPa	70	100	150	200	250
Compressive strength @ 1% nominal strain	kPa	20	45	70	90	100
Bending strength	kPa	115	150	200	250	350
Moisture properties						
Water vapour diffusion resistance factor, μ		20-40	30-70	30-70	40-100	40-100
Water vapour permeability, δ	mg/ (Pa*h*m)	0.018-0.036	0.010-0.024	0.010-0.024	0.007-0.018	0.007-0.018
Vapour resistivity	MNs/ (g*m)	145	200	238	238	238
Thermal Properties						
Thermal conductivity	W/(m*K), (at 10ºC)	0.038	0.036	0.035	0.034	0.034
Thermal resistivity	(m*K)/W (at 10ºC)	26.32	27.78	28.57	29.41	29.41
Other properties						
Nominal density	kg/m³	15	20	25	30	35

Other classes are used in other parts of the world e.g. in Australia the following 6 classes are used in accordance with the standard AS 1366 (with the compressive stress at 10% deformation in brackets): L (50), SL (70), S (85), M (105), H (135), VH (165) (Isolite, 2011).

The different properties are dependent on the physical environment. For example, the thermal conductivity will be dependent on the temperature and the humidity. When comparing properties of insulation material it is therefore essential that the properties are determined under similar conditions, or that due caution is exercised in the comparisons.

Grades with graphite

Besides differences in density, EPS, graded with improved thermal performance due to addition of particles are marketed. Several types with up to 20 % better insulating performance than conventional EPS are marketed (e.g. under thetrade names ThermaWallSilver™ and Neopor®). The improved insulative performance comes from minute particles of graphite mixed with EPS that act as infrared reflectors that reduce thermal conductivity.

Main technical advantages

The main technical advantages of EPS as insulation material in the construction sector as described by market actors are the following:

- Low weight, high compression strength, good walkability;
- High insulation value, relatively constant over time;
- Resistance to water and water vapour (the resistance of the XPS is higher).
- Moderate effect of moisture on insulation value;

- Non fibrous. No irritation to skin, eyes and lungs, from releases fibres and dust; no personal protection equipment needed;
- Does not degenerate by moisture, rotting or mould and do not compact by vibration;
- Easy to cut and shape.

Potential disadvantages of the EPS are assessed further in the subsequent chapters.

Recyclability

According to industry, the most appropriate treatment recommended for end-of-life HBCDD-containing EPS is state-of-the-art incineration with energy recovery (EUMEPS, 2010). In the assessment of EPS and alternatives in lifecycle perspective in Chapter 7 it will be assumed that EPS insulation boards are disposed of for incineration with energy recovery

EPS can be recycled and post-consumer EPS is in some countries collected and recycled. In Europe EPS (mainly packaging material) is collected through a Europe-wide network of collection points, organised both by local authorities and commercial enterprises. The recycled EPS may be used for manufacturing of new boards (normally to below 25 percent recycled material), non-foam applications such as coat hangars, flower pots, park benches or fence posts or reground and mixed with concrete to produce building products such as prefabricated light weight concrete blocks (EUMEPS, 2011b)

The majority of recycled EPS is manufacturing waste or post-consumer packaging material without flame retardants. EPS insulation boards in buildings last for long time, and still only a small quantity is disposed of today. If recycled, the flame retarded EPS should be separated from other types of EPS and used for applications where flame retardancy is required. To the knowledge of the authors no collection systems for separate collection and recycling of post-consumer flare retarded EPS exist, but in principle systems could be developed where recycled flame retarded EPS is separated from other EPS e.g. on the basis of the presence of bromine.

3.3 Application areas for flame retarded EPS in buildings

EPS is used in buildings in a broad variety of applications.

The following applications have been indicated for Europe (EUMEPS and other sources):

- Roofs and lofts:
    - Flat and pitched roof insulation;
    - Loft insulation.
- Floors:
    - Floor insulation as ‘slab-on-ground’ insulation, as blocks between concrete beams and radon control systems ;
    - Floor heating systems;
    - Sound insulation in floating floors (to avoid transmission of contact sound).
- Walls:
    - Interior wall insulation combined with gypsum board;
    - Exterior wall insulation or ETICS (External Insulated Composite Systems, e.g. rendered façades) and cavity wall insulation (boards and loose fill);

  - Core material for sandwich and stressed skin panels (metal and wood fibreboard);
  - Void forming systems.
- Foundations:
  - Insulated concrete forms (ICF), foundation systems and other void forming systems ;
  - Load bearing foundation applications;
  - Civil engineering applications such as void-fill blocks and substructures.
- In cold stores and as thermal insulation for building equipment and industrial applications (e.g. in cryogen installations).

Besides the applications in building (addressed in this study), EPS is used for a range of applications in other construction and civil engineering applications.

As mentioned above, approximately 70 % of EPS used for construction applications in Western Europe is flame-retarded grades. For some applications e.g. below concrete floors, in many countries EPS without flame retardants are used. In some countries, however, according to the building regulations, flame retarded grades are required for all the mentioned applications in buildings as further discussed in Chapter 6.

According to a market report, EPS consumption share by application in construction industry shows 40% for sidewalls, 30% percent was consumed for roofing, and 17 and 13% for concrete blocks and basements respectively in 2006 (Frost & Sullivan, 2007).

Table 3.2 gives an overview of the different applications of the EPS types in a matrix prepared by EUMEPS (2011). The applications are taken from the standard ISO TR 9774. According to EUMEPS, the matrix covers probably 95% of all the known building insulation EPS applications. Bullet points indicates possible and most used applications/product types combinations; to the left of these the EPS properties are too low for a reliable application; to the right from the bullet points the quality may be too good in relation to the price.

The most widely used product types are in the EPS 60 to 100 range.

Table 3.2 Overview of examples of applications and EPS product types (EUMEPS, 2011a)

Application versus EPS type	EPS S	EPS 60-100	EPS 100-150	EPS 150-200	EPS 200-250	EPS 250-300	EPS T
CELLARS							
Internal insulation	•	•	–	–	–	–	–
External, protected	=	=	•	•	–	–	–
Perimeter insulation	=	=	•[+])	•[+])	•[+])	–	–
GROUND FLOORS							
Slab- on- ground	=	•	•	•	•	–	–
Concrete floor element	=	•	•	–	–	–	–
On construction floor	=	•	•	–	–	–	•
Renovation el.	=	•[1])	•	–	–	–	–
FLOORS							
Ceilings/ loft insulation	=	•	–	–	–	–	–
Floating floors	=	•	•	•	–	–	•
WALLS/GABLES							
Doublage	•	–	–	–	–	–	•
SIPS / others	=	•	•	–	–	–	–
Cavity wall insulation	•	•[+])	•	–	–	–	–
Sandwich panels-steel	=	•	•	–	–	–	–
External insulation	•	•	–	–	–	–	•
ETICS	=	•[+])	•	–	–	–	–
PITCHED ROOFS							
Internal-insulation (all)	=	•	–	–	–	–	–
Sandwich panels (all)	=	•	–	–	–	–	–
External insulation	=	•	•[2])	•[2])	–	–	–
FLAT ROOFS							
Warm roofs	=	•[1])	•	•	•	–	–
Cold roofs	=	•	•	–	–	–	–
Inverted roofs	=	=	=	•	–	–	–
CIVIL ENG APPL.							
All/ general	=	•	•	•	•	•	–

Legend:

• normally used in the EUMEPS member states.

= not possible from functional requirements.

- not necessary / applied normally unless properties are explicitly needed.

1) when load distribution boards are applied.

2) when load bearing.

Depending on the “local” building regulations the properties required may be more severe (indicated: +) than given in EN 13163

EPS S: for non load bearing applications where there is no compressive stress required.

Use in tropical areas

Whereas in Europe the main purpose of the use of the EPS is the insulation against cold during winter, in other parts of the world insulation is used in order to reduce the energy consumption for air-conditioning.

The main difference when looking at the product range from manufacturers in Europe and Australia (e.g. RMAX, 2011) is that the products for insulation of the cellars and foundations are less common in Australia, as they are less needed in warm climates. The product range still includes EPS insulation boards for cavity walls, external cladding, sandwich constructions, roofs and ceiling panels. Particular applications are e.g. the use of EPS for wall cladding where the rendered EPS forms the outer cladding.

EPS marketed for buildings in the Middle East seems more or less to be used for the same applications as in Australia including EPS sheets for roofs, floors and wall insulation, insulated concrete elements and sandwich elements (Middle East Insulation, 2011).

A particular situation exist for insulation used on humid tropical areas as the insulation materials under these conditions should absorb as little water as possible as the water negatively influence the thermal properties of the insulation materials and may lead to degradation. For these applications more compact panels in the EPS 200-250 range are marketed as exemplified with the Peripor® product range marketed in Malaysia (BASF, 2011). Whereas the EPS 200-250 in Europe is marketed mainly for cellars, floors and warm roods (Table 3.2), this type is in humid tropical areas marketed for the full range of insulation applications including external wall insulation and cavity insulation.

Application areas for EPS vs. other insulation materials

Application areas for EPS and other selected insulation materials according to the German standard DIN V 4108-10 are shown in Table 3.5. The data has been summarised by the GDI, the German umbrella organisation of associations in the insulation industry (GDI, 2007). One or more alternative materials are applicable for all applications of EPS, with the reservation that for some applications a general approval by the building authorities of the insulation material is required. It should be noted that some application areas for which heavy mineral wool is marketed (e.g. slabs-on-ground), are not indicated in the table. The wood wool boards mentioned in the table are of the relatively rough, heavy type with concrete or magnesite binder, not to be confused with the type assessed further in this report.

For applications where the insulation material is in direct contract with the ground (perimeter insulation), EPS and in particular XPS have some advantages as compared with most other insulation materials. For these applications, the insulation material is typically placed between a concrete slab and the insulation material is well protected from fire exposure. In this construction there is no advantage of using fire resistant materials or flame retarded plastic foams although it may be required in some countries. As flame retardants are not needed for this construction, perimeter insulation will not be further discussed in the next chapter on alternatives to flame retarded EPS in buildings.

Table 3.3 Application areas for different insulation materials according to the German standard DIN V 4108-10 (after GDI, 2007)

Application area	Mineral wool	EPS	XPS	PUR	Wood wool
Pitched roof					
On the rafter	●	●	●	●	●
Between the rafter	●	●	-	●	-
Below the rafter	●	●	●	●	●
Flat roof					
Sloping roof	●	●	-	●	-
Green roof	only DAA *	only DAA *	●	only DAA*	-
Parking deck	-	only DAA * a)	● a)	only DAA *a)	-
Roof terrace	-	only DAA*	●	only DAA*	-
Steel profile tin roof	●	●	only DAA	●	-
Ceiling/floor					
Top ceiling - walkable	b)	b)	●	b)	●
Top ceiling - not walkable	●	●	Only DI **	●	●
Basement ceiling	●	●	●	●	●
Floor - below screed without requirements for footfall noise reduction	●	●	●	●	●
Floor - below screed with footfall noise requirements	●	●	-	-	-
Industry floors	-	●	●	●	●
Walls					
Internal insulation	●	●	●	●	●
Cavity insulation	●	●	●	●	
ETICS (external thermal insulation composite systems)	c)	c)	-	c)	c)
Base insulation – thermal bridge insulation	●	●	●	●	●
Ventilated façades	●	●	●	●	●
Wood and timber frame building	●	●	-	●	●
House partition walls with requirements for noise reduction	●	c)	-	-	-
Room partitioning wall	●	-	-	-	●
Perimeter					
Floor batt against the ground	-	c), d)	● d)	c)	-
Wall against the ground	-	c)	● e)	c)	-

* Only for roofs where the insulation is under seal which protect against the weather (DAA) – not for inverted roofs where the insulation is not protected (DUK).

** Only for internal insulation of the ceiling (the underside) or the roof, insulation at rafter / support structure, suspended ceilings, etc (DI)

a) Insulation must meet the requirements regarding static/dynamic compressive strength/pressure resistance. Manufacturer's instructions must be observed.

b) Additional load-distributing layer required.

c) Regulated by general approvals by the building authorities

d) Additional general approvals by the building authorities regarding weight-carrying foundation slabs.

e) Additional general approvals by the building authorities when used in water under pressure.

Original includes also abbreviations on application type and data on multi—layered wood wool boards.

Examples of applications areas where EPS has specific advantages

For some general applications like cavity insulation or insulation of pitched roofs a large variety of insulation materials are used and the EPS is in many parts of the world not in particular the material of choice. The combination of the low weight of the EPS and the relatively low effect of moisture on insulation value makes EPS attractive for a number of applications.

An indication of industry's consideration about the use of EPS is the recommendations on the use of insulation materials from manufacturers, who manufacture both EPS and other insulation materials. The following applications are indicated by a large French manufacturer. Similar indications of the use of EPS/XPS for flat roof and floor insulation can be found from other manufacturers that manufacture a range of insulation materials.

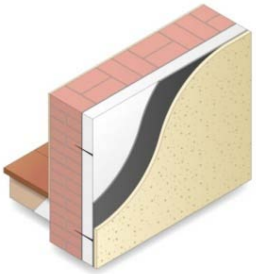
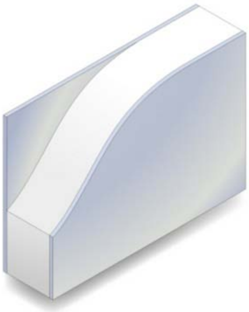
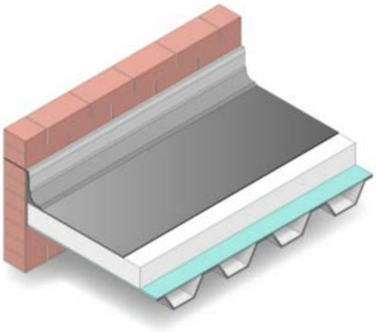
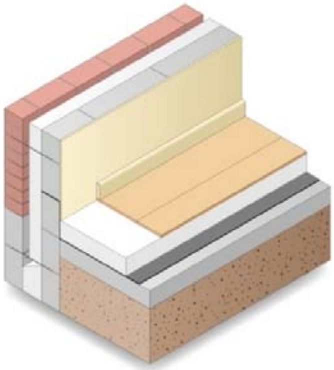
Table 3.4 Application areas for different insulation materials (Isover, 2011)

Material	Characteristics and properties	Main applications
Glass wool	Lambda (λ) (thermal conductivity) Acoustic Flexible and light Not very expensive	Roofs (including blowing) Walls (excluding external thermal insulation under rendering) Cladding Ceilings and partitions
Stone wool	Mechanical Fire resistant Acoustic	Sandwich panel Steel frame roof Floor (acoustic)
EPS, XPS	Mechanical Lambda (λ) (thermal conductivity) Water resistant	External thermal insulation under rendering Floor (thermal) Terrace roof
Alternative insulation	Status value, image Use of biomass or sub-products	Roofs Walls

Other applications where EPS is regarded as particular attractive (and has a significant market share) are shown in the table below. Flame retarded XPS is typically used for the same application and as mentioned above XPS is particularly suitable for applications where high mechanical and water resistance is required.

In the assessments in the following chapter specific attention will be given to these applications.

Table 3.5 Applications of flame retarded EPS discussed in more detail in the following chapters (EPS is the white material) (Source: Sundolitt Ltd. at http://www.sundolitt.co.uk)

 External façade insulation (ETICS)	 Sandwich panels
	
Flat roof insulation (in particular where the insulation is placed on top of the waterproofing membrane)	Floor insulation e.g. for floating floor

4. Alternatives to flame retarded EPS in buildings

A variety of insulation materials are used in buildings, each having some advantages for specific applications determining its use, and many with general application. In terms of market volumes the major insulation materials apart from the EPS/EXS are mineral wool, fibre glass wool and polyurethane rigid foams, but a number of other insulation materials are used to some extent.

The following alternative materials and techniques are shortly described in this chapter:

- Non-flame retarded EPS in fire-resistive construction;
- Mineral wool: Stone wool and glass wool (in blankets and loose fill);
- Plastic foams: Polyurethane rigid foams (PUR and PIR) and phenolic foams;
- Natural fibre based insulation materials (wood fibre, flax, hemp, cellulose/paper, sheep's wool, etc.);
- Other insulation materials (cellular or foamed glass, aerogel , etc.).

Materials and techniques, which are suitable as alternatives for the key applications of the EPS, will be further described and assessed in the later chapters.

4.1 Fire-resistive construction with non-flame retarded EPS sheets

Non-flame retarded EPS boards are used in a number of countries in combination with other construction materials which protect the EPS from catching fire. A widely applied construction is as ground or floor insulation below a concrete layer, but also walls and other more open constructions may be made with regular EPS boards which are not flame retarded if thermal barriers are applied.

International building fire safety regulation relevant for EPS is described in Chapter 6 and examples of the use of non-flame retarded EPS in fire-resistive construction are included in the same chapter.

4.2 Stone wool

Stone wool is made from volcanic rock, typically basalt or dolomite, an increasing proportion of which is recycled material in the form of briquettes. Slag wool is made from blast furnace slag (waste). The stone wool is a subgroup of the mineral wool together with glass wool. Over the last decade, glass wool, rock (stone) wool and slag wool have together met just over half of the world demand for insulation.

After the furnace, droplets of the vitreous melt are spun into fibres. Droplets fall onto rapidly rotating flywheels or the mixture is drawn through tiny holes in rapidly rotating spinners which shapes it into fibres. Small quantities of binding agents are added to the fibres for adhesion. The structure and density of the product can be adapted to its precise final usage. Inorganic rock or slag is the main components (typically 98%) of stone wool. The remaining 2% organic content is generally a thermosetting resin binder (an adhesive), usually phenol formaldehyde and a little mineral oil.

Market for mineral wool

In Europe the mineral wools take up about 50% of the insulation market while in Asia they account on for about 20% which may reflect tradition and differences in building requirements.

Table 4.1 Insulation market in Asia and Europe (Rockwool, 2011d)

	Market size (EUR)	Plastic foams	Stone wool	Glass wool	Other
Asia	2.5 bill.	72%	8%	12%	8%
Europe	6.5 bill.	40-45 %	25-30%	25-30%	5%

In Europe 88% of glass wool and 80% of stone and slag wool are used in the construction of residential and commercial buildings; 12% of glass wool and 20% of rock (stone) and slag wool are used in industrial applications, including heating, ventilation and air conditioning, household appliances and transportation (Floyd *et al*., 2008).

Applications areas in buildings

Stone wool is available as blankets (batts and rolls) and as loose fill.

Common application of mineral wool for building insulation include (Eurima , 2011):

- Loft insulation ;
- Cavity wall insulation (loose fill or batts);
- Internal wall insulation;
- External wall insulation;
- Flat roof insulation;
- The insulation of heating systems;
- Hot and cold water services.
- Stone wool is available in range of qualities with differences in density and stiffness. The range of density range from 45 – 140 kg/m^3 . The compressive strength increases with increased density.
- Examples of types marketed for applications identical to key EPS applications include:
- Roofing boards with high density rigid top surface for warm flat roofs;
- Foundation boards of water-repelling dense stone wool;
- Dual density batt which has been specifically developed for rainscreen and overcladding applications;
- Dual density thermal insulation boards with high point load compressive strength for floors and rood decks.
- Wide range of sandwich panels with core of stone wool.

Loose-fill insulation is typically blown into place or spray-applied by special equipment. It can be used to fill existing wall cavities and for irregularly shaped areas and is an alternative to EPS loose fill.

Properties

The main advantages of stone wool insulation materials as compared to other insulation materials, as highlighted by manufactures of the materials, include:

- Good fire insulation. Stone wool products are in general classified in Euroclass A2 (No significant contribution to fire growth). Resists high temperatures;
- Water repellent (some types);

- Combat noise;
- No maintenance.

Recyclability
Both manufacturing waste and post consumer waste of stone wool can be recycled for manufacturing of new stone wool. The resources of the virgin raw material for the production the stone wool (rock) is abundant, and the main driver for the recycling is to reduce the quantities of waste for landfilling and save energy resources needed for exploiting the virgin materials. Besides waste of stone wool, waste from other industries is increasingly used for manufacturing new stone wool insulation products. The main challenge in the recycling of post consumer stone wool is the logistics as concern the collection and transport of the materials. Recycling systems for stone wool cut of waste from the construction sites exist in e.g. Denmark and Germany. Similar systems for post consumer recycling of stone wool have not been identified. The general pattern is that stone wool is disposed of to landfill.

4.3 Glass wool (fibre glass insulation)

For glass wool the raw materials are sand, limestone and soda ash, as well as recycled off cuts from the production process. The glass wool is a subgroup of the mineral wool.

The raw materials are melted in a furnace at very high temperatures, typically 1300 to 1500 °C. In insulation fibre glass borates act as a powerful flux in the melt as it lowers glass batch melting temperatures (Floyd et al., 2008). After the furnace, droplets of the vitreous melt fall onto rapidly rotating flywheels or the mixture is drawn through tiny holes in rapidly rotating spinners which shapes it into fibres for adhesion. Small quantities of binding agents are added to the fibres. Glass wool products usually contain 95% to 96% inorganic material (Eurima, 2011).

Applications areas in buildings
Glass wool is available as blankets (batts and rolls) and as loose fill.

The glass wool insulation is produced in a variety of densities according to format and function. Varying densities result in varying levels of thermal conductivity. Applications include masonry cavity walls, timber frame walls, roof rafter insulation, flat roofs, loft and suspended floor insulation .

The major applications of the glass wool are for pinched roofs, cavity walls and as sound deadening floor insulation for which it is a relatively low-cost solution. The glass wool is like the stone wool also marketed for the applications indicated as key EPS applications such as insulation of flat roofs, foundations, external wall insulation and sandwich panels.

Loose-fill insulation is typically blown into place or spray-applied by special equipment. It can be used to fill existing wall cavities and for irregularly shaped areas and is an alternative to EPS loose fill.

Glass wool designed for use in tropical conditions are among other marketed in the Pink® Batts® insulation range by a New Zeeland company (Tasman, 2011). The glass wool can be installed in combination with an infrared reflecting building foil to form a sealed vapour barrier around the insulation and building structure. The glass wool is used for the same applications as know from temperate zones.

Properties
Glass wool has many of the same advantages as the stone wool when compared to other insulation materials: non-combustible, good sound reduction properties, flexible and non-degradable.

Recyclability

Glass wool is to a large extent produced from recycled glass. Recycled window, automotive or bottle glass is increasingly used in the manufacture of glass wool and it now accounts for 30% to 60% of the raw material input. In some plants this is as high as 80% (Eurima, 2011). Manufacturing waste is often recycled in the production process and this process is also applicable for post consumer waste. As for the stone wool, the main driver for the recycling of waste products is to reduce the quantities of waste for landfilling and save energy resources for exploiting the virgin raw materials. The main challenge in the recycling of post consumer glass wool is the logistics as concern the collection and transport of the materials. Post consumer recycling systems for glass wool have not been identified. The general pattern is that glass wool is disposed of to landfill.Polyurethane foam (PUR and PIR)

Two groups of rigid polyurethane foams are used, designated PUR and PIR foams. In the PUR foams the isocyanate is reacted with a polyether polyol , whereas in the PIR foams a lower-cost polyester derived polyol is used in the reaction. In the PIR foams the proportion of methylene diphenyl diisocyanate (MDI) is higher than for PUR and the isocyanates polymerise to some extent into polyisocyanurate. The foams are designated “polyisocyanorate” or “polyiso”. For insulation in buildings the PIR foams takes up the majority of the market.

The PUR/PIR foams are used in various ways:

- Factory made insulation boards or blocks;
- In combination with various rigid facings as a constructional material or sandwich panel;
- As spray insulation, foamed directly on the building site;
- As pipe insulation.

Applications areas in buildings

PUR/PIR foams are widely used in the construction sector. The consumption of PUR/PIR foams for the construction sector in the EU, Norway and Switzerland in 2004 is reported at 590,000 tons; nearly the same as the reported consumption of EPS for this sector (GUA, 2006). Also in North America and other parts of the world the rigid PUR/PIR foams are some of the most used insulation materials for buildings.

The PUR/PIR foam sheets are marketed for many of the same applications in buildings as the EPS. A comparison of the distribution of EPS, XPS and PUR (PUR/PIR) on applications in buildings in Germany illustrates, however, shows some differences in distribution between the different applications (Table 4.2). The authors of the report (GUA, 2006) note that the market share of PUR-boards for insulation of external walls is atypically low in Germany.

Table 4.2 Distribution of EPS, XPS and PUR insulation boards by application in buildings in Germany (Gesamtverband Dämmstoffindustrie as cited by GUA, 2006)

Application	EPS	XPS	PUR
External wall	39%	38%	6% *
Floor construction	41%	38%	25%
Flat roof	13%	18%	10%
Pitched roof	1%	1%	37%
Others	6%	5%	22%

* Note in GUA (2006): Several experts confirmed that the market share of PUR-boards for insulation of external walls is atypically low in Germany.

The PUR/PIR foams share some of the key properties with the EPS as regard low density and good water resistance. For this reason the PUR/PIR foams are applicable for most of the applications where EPS has a significant market share.

Properties

The main technical advantages of the rigid PUR/PIR foams as highlighted by manufactures of the foams include:

- Low thermal conductivity. PUR/PIR foams are among the insulation materials with the lowest thermal conductivity and the insulation layer can consequently be thinner that with most other materials.
- Lightweight.
- Moisture resistant. Closed cell structure which eliminates risk of water penetration and make the insulation capacity less affected by air movement or moisture.
- Stable and durable. The materials PUR/PIR foams are thermoset materials and consequently have dimensional stability and are resistant to many organic solvents in adhesives, paints, etc. Stable at elevated temperatures. Has a high compressive strength.
- Non fibrous. There is no need for personal protective equipment when applying the foams boards and they do not release fibres during use.

The rigid PUR/PIR foams are manufactured in a range of densities for different application areas (typically 30-45 kg/m3, however it can reach 100 kg/m^3 for some applications).

As for the EPS, the properties of the PUR/PIR foams depends on the density of the foams, but are also dependent on the blowing agent (cell gas) used.

Recyclability

As the PUR/PIR foams are thermosets, they cannot be remelted. Most grades of PUR/PIR foam cannot be produced from recycled materials. The foams can be crushed and made into pressed boards made of downcycled PUR used for special applications for example floor constructions. Furthermore particles from grinded foam can be used as filler or in combination with cement as insulating mortar (Bing 2006). No data has been available indicating to what extent the post-consumer PUR/PIR foams are actually recycled, and probably the majority of the foams are disposed of for landfilling or incineration with or without energy recovery.

4.4 Phenolic foams

Phenolic foam insulation is made by combining phenol-formaldehyde resin with a foaming agent. When hardener is added to the mix and rapidly stirred, the exothermic reaction of the resin, in combination with the action of the foaming agent, causes foaming of the resin. This is followed by rapid setting of the foamed material. (Greenspec, 2011). In the process phenol is polymerized by substituting formaldehyde on the phenol's aromatic ring via a condensation reaction and a rigid thermoset material is formed. Compared to the EPS/XPS and PUR/PIR, the market share of the phenolic foams seems to be small due to higher prices.

Use areas

Phenolic foam has been used in structural applications for over 20 years. The closed cell, rigid thermoset phenolic foams share some of the key properties with the EPS as regard low density and water resistance. For this reason the phenolic foams are applicable for most of the applications where EPS has a significant market share.

Phenolic foam insulation boards are used for building and construction, in roofing (pitched and flat roofs), cavity board, external wall board, plasterboard dry lining systems, wall insulation, floor insulation and as a sarking (EPFA, 2011).

Properties

Advantages of phenolic foams according to market actors include (EPFA, 2011 and Foamsales, 2011):

- Low thermal conductivity. With a thermal conductivity of 0.020-0.023 W/(m·K) rigid phenolic insulation is the most thermally efficient insulation product commonly available. Allows for the use of thinner panels where saving space is a requirement.
- Good fire resistance, low smoke emissions and low levels of toxic gas emission. No dripping of foam during combustion.
- Unaffected by air movement, resistant to the passage of moisture vapour. Has low water absorption which takes place predominantly in the cut/broken surface cells of the foam
- Non fibrous and easy to handle and install. Personal protection equipment is not required during mounting.
- High strength to density ratio as well as a good compressive strength.
- Good chemical resistance. Phenolic foam is unaffected by oils, fuels, turpentine, benzene and ethanol and many organic solvents.

Phenolic foams are marketed for many of the key application areas of EPS and have many of the same advantages as flame retarded EPS.

4.5 Natural fibre-based insulation materials

Various modern insulation materials are based on natural fibres, primarily plant fibres but also sheep wool. Some of these have been known for centuries but have got a renaissance over the last decades with the growing interest for environment friendly building techniques. They are available as loose insulation fill, as insulation batts or/and as rolls.

No data has been available of the global market for the natural fibre-based insulation materials, but at the German market in 2006 the insulation materials made from renewable raw materials accounted for 4% of the total market. The main materials were cellulose (32% of total renewable), wood fibre (28%), wood wool panels (20%), flax/hemp (9%), sheep’s wool (4%), while other materials took up 7% of the total (Hemp, 2007).

It has been beyond the limits of this study to describe in detail all these insulation materials. A closer description and a summary of advantages and disadvantages of various natural fibre-based insulation materials can be found in the directory of “green” building products at the website of GreenSpec® , UK. (GreenSpec, 2011).

The insulation materials have in common that they are produced from renewable resources, and that the non-renewable energy used to produce the materials is relatively low, resulting in relatively low CO_2 emission during their lifecycle. Many of the materials are somewhat sensitive to moisture. Furthermore they may be sensitive to microbial degradation if permanently wet. Some of the materials may be used as alternatives to EPS for some applications of EPS, but for many of the key applications of EPS, the lower moisture resistance of the materials limits there use.

Based on the available data on applications and technical properties from the literature, GreenSpec® and manufacturers websites, wood fibre insulation boards has been selected as an example for further assessment although some of the other materials could be suitable for some applications as well.

4.5.1 Wood fibre insulation boards

Wet-formed wood fibre insulation board is made from compressed wood fibres only or made with a binder of polyurethane (PUR) or a polyolefin. It may be treated with paraffin in small concentrations to increase water resistance, and/or coated with latex on one side for moisture control or by other materials for rendering.

Wet-formed wood fibre board insulation is made from mainly pre-consumer waste wood from saw mills. The wood is chopped to chips and then milled in water before being pressed and dried with or without additional bonding agents. It exists in different thicknesses (20- 240 mm or more) and densities. For sarking applications, latex is added to provide water-proofing properties. For outer walls finishes with rendering are available (Naturepro, 2011).

Applications

Wood fibre insulation boards have a long history. In resent decades they are experiencing a revival in green building due to their relatively low environmental impact. Wood fibre board insulation has a variety of applications in housing, of which many are in common with EPS: outer and inner walls, floors, ground floors, ceilings, flat roofs, pitched roofs, etc. (see for example Gutex, 2011). Also used in breathing wall construction and as insulated sarking (GreenSpec, 2011). Wood fibre boards are also used in combination with other insulation materials including EPS in compound insulation boards (Knauf, 2011).

Examples of wood fibre board products and selected data are presented in Section 5.7.2.

Recyclability

Wood fibre insulation board can in principle be reused directly if in good condition. The intrinsic energy in the material can be exploited with waste incineration with energy recovery. Being mainly wood, this energy is carbon neutral if the trees are grown sustainably. If the material is landfilled the wood part, most or all of it, depending on product type, will degrade to mineral components, again carbon-neutrally.

4.5.2 Other natural fibre-based insulation materials

As mentioned, a number of the other natural fibre-based insulation materials have been considered as alternatives to flame retarded EPS, but not further assessed due to limitations of the study.

Wood wool

Wood wool is made from wood fibres only (loose fibre fill), bonded by polyolefin fibres (insulation batts) or formed into boards bonded with concrete or a magnesite binder (Greenspec, 2011, Danish Wood Insulation, 2011; GDI, 2007). The loose fibre fill and insulation bats are fire retarded, usually with ammonium phosphate. Wood fibre insulation is used in inner and outer wall construction, ventilated pitched roofs and in ceilings and floors. The wood source is forestry thinnings and saw mill residue (Greenspec, 2011, Danish Wood Insulation, 2011).

Cellulose (/paper) insulation

Cellulose insulation, sometimes called paper insulation, is made from recycled newspaper. The material is treated with fire retardants, usually aluminium hydroxide and a mixture of borax and boric acid which also repel insects and fungi. The concentrations of fire retardants may vary, but one example is 9% (wt/wt) aluminium hydroxide and 3% boron salts (energi-isolering.dk, 2011). The insulation is suitable for use in ceilings, between rafters and joists and timber wall construction. Cellulose insulation is available in a loose format for pouring and dry or damp spraying as well as in battsfor fitting within metal or timber frames (Greenspec, 2011).

Sheep's wool insulation

Sheep’s wool batts and rolls are made from wool, in some cases also with a polyester binder and treated for insect resistance with for example boron salts applied in a latex binder. An example of an approximate composition is: Sheep’s wool (>90%), borax salt (<10%), natural rubber (<10%), calcium oxide, iron Oxide, and alumina (<1%). Wool is used for a variety of purposes, for example as insulation between rafters, joists and timber studs in innenr and outer wall construction. Sheep’s wool has good hygroscopic properties that help to moderate temperatures throughout the seasons. Due to its natural characteristics wool has an inherent fire resistance to which the borax contents add further resistance (Greenspec, 2011; Sheep Wool Insulation, 2011).

Hemp insulation

Hemp insulation is available in mats and rolls. It is made from hemp or hemp mixed with either recycled cotton fibres, or wood fibres, bound with a polyester binder and treated for fire resistance. Hemp insulation is used in wall construction, ventilated pitched roofs and in ceilings and floors. Hemp insulation is treated with an ammonium phosphate based fire retardant (Greenspec, 2011; Naturepro, 2011). It is recommended by producers to be used in conjunction with a vapour permeable membrane. Hemp insulation has in earlier years mainly been applied by green builders, but recently, major insulation producers have brought it into their product programme and it could perhaps reach a wider application.

Flax insulation

Flax insulation batts and rolls are made from flax with a polyester binder and treated for fire resistance. Flax insulation is used in wall construction, ventilated pitched roofs and in ceilings and floors. Contains boron-based flame retardant which also acts as a biocide (Greenspec, 2011). Examples of thicknesses available: 50-150mm (Isolina, 2011).

Cork insulation

Cork insulation is made from cork oak bark which is harvested from the tree every 25 years. Cork granules are expanded and then formed into blocks, using the natural resin, through high temperature and pressure. The most common applications for cork insulation are in flat roofs and insulated render systems, both of which take advantage of cork’s dimensional stability and resistance to compression (Greenspec, 2011).

Other organic insulation materials

In addition to the insulation materials mentioned above also hempcrete and coconut fibre board exist. These are all organic material with a cement binder, which have some insulation capacity. Also straw is used for insulation purposed in green building, applying special construction techniques. These insulation materials are not dealt further with in this report.

4.6 Other insulation materials

Various other insulation materials made from mineral raw materials are marketed and may be used as alternatives to EPS for specific applications.

4.6.1 Cellular glass insulation

Cellular, or foamed, glass insulation is made from crushed glass that is mixed with carbon and heated to 1000ºC. The heat causes the carbon to oxidise to form the characteristic bubbles. One of the producers reports that more than 60 percent of the glass used is recycled glass from cars and the windows industry.

Foamed glass has a very high compressive strength which, combined with its water and vapour resistance, makes the insulation blocks or boards suitable for flat roofing in high-load situations such as retaining walls, car parks and green roofs. The material is also available in lighter qualities suitable for ventilated façades, bearing and non-bearing walls, ceilings and floors (Greenspec, 2011; Foamglas, 2011). Cellular glass is produced several places globally, including in USA and China.

The cellular glass is among other used in rooms where high degree of air purity is required (museums, hospitals, high tech production facilities, etc.) and in locations with special bacteriological and hygienic requirements (food processing facilities, swimming pools, etc.) .

Examples of cellular glass qualities and selected data are shown in Section 5.7.3. Cellular glass was selected for further study in this report as an example of a mineral insulation material with increasing application.

Recycling

The cellular glass consists of pure glass and can be recycled. No data on actual post-consumer recycling of foamglass has been obtained, and the small amount that currently may be disposed of is probably landfilled.

European facilities use 30% or more post-consumer recycled glass content in the production of Foamglas® insulation. The maximum of recycled glass used for manufacturing is currently approx. 66 percent. According to an EPD for one product, the recycled glass from car windscreens and TV- and computer monitors constitutes 37% of the raw materials (Foamglas, date not indicated).

4.6.2 Aerogel insulation

Aerogel is a lightweight, low-density material made from silica and air. Aerogel is relatively new on the market. Aerogel blankets are available alone or as a as a component in laminate panels bonded to boards including plasterboard, wood fibre reinforced gypsum board, plywood, and chipboard. The panels are distinguished by their very high insulation capacities. The material is hydrophobic (Greenspec, 2011; Aspen Aerogels, 2011).

Aerogels are made by drying wet gels under moderate temperatures and high pressures, which replace the liquids in the gels with gas, leaving behind continuous networks of strands made of nanometer-sized beads. The solid tangle of fibres and infinitesimal air pores that comprise aerogels result in very good thermal, acoustic and electrical insulating qualities (Physorg, 2005).

Aerogel has the following composition: Methylsilylated silica (40-50%), polyethylene terephthalate (PET or polyester) (10-20%), fibrous glass (10-20%) and magnesium hydroxide (0-5%). (Aspen Aerogels, 2009). Dust should not be inhaled and skin contact should be avoided.

4.6.3 Perlite

Perlite is made from naturally occurring rock with a natural water content which makes it foam at high temperatures. It is used a loose fill in cavity walls, in floors, etc. Used in concrete it can form lightweight, insulated floors. It can also be aggregated with water glass to form solid boards and other forms, used for example in high temperature industrial applications. Perlite is naturally fire resistant (Nordisk Perlite, 2011; Perlite.org, 2011).

4.6.4 Other inorganic insulating materials

In addition to the above mentioned, also lightweight concrete and lightweight aggregates (expanded clay) have insulation properties and they are common building materials. They are mainly used for special purposes such as bathroom walls and building foundations, respectively, and are therefore not described further in this report. In some cases lightweight aggregates can however be used for ground floor and flat roof insulation.

A number of specialty insulation materials used in industrial applications and for high-temperature purposes exist, but these are not described further in this report.

4.7 Summary and selection of alternatives for further assessment

Table 2.2 provides an overview of selected properties of the considered insulation materials.

The materials selected for the more detailed assessment in the remaining part of the report are marked in gray in the table. For some of the non-selected materials, the table may include information from the literature or manufacturer’s websites that have not been described in detail in the previous sections.

The insulation materials were chosen to match the applications of flame retarded EPS as well as possible, with the following remarks:

- Stone wool was selected as a representative of the relatively similar mineral wools.
- PUR/PIR was selected as representative of plastic foam materials, as it seems to be the main competitor to flame retarded EPS among these foams
- Wood fibre insulation board was selected as a representative of the renewable organic fibre materials as the material is used for many of the same applications as the EPS.
- Cellular glass was selected as a representative of up-coming insulation materials with very high compressive strength.

Table 4.3 Summary of considered properties (selected insulation materials marked in bold)

Technical solution	Thermal conductivity, W/(m·K) *	Density, kg/m^3 *	Compressive strength (low, medium, high)	Water resistance (+,-)	Form (**S**labs/boards, **M**ats/batts, **R**olls, **L**oose fill)	Key EPS applications (Exterior **w**all /Flat **R**oofs /**F**loors /**S**andwich elements
Flame retarded EPS sheets	0.028-0.036	15-35	Medium	-/+	S, L	W,RF,S
Non-flame retarded EPS sheets	0.028-0.036	15-35	Medium	-/+	S, L	W,RF,S
Stone wool	0.031-0.040	24-105	Low-medium	+	M,L	W,RF,S
Glass wool	0.031-0.040	16-24	Low-medium	+	M,R,L	W,RF,S
PUR/PIR	0.022-0.028	30-40	Medium	+	S	W,RF,S
Phenolic foams	0.02-0.023	60-160	Medium	-/+	S	W,RF,S
Wood fibre insulation board	0.037-0.050	110-240	Low-medium	-	S	W,R,F
Wood wool	0.038-0.090	50	Low	-	M, L	W,F
Cellulose (paper) insulation	0.038-0.040	32	Low	-	L	W,F
Sheep's wool	0.039-0.040	25	Low	+	R, (M?)	W,F
Hemp insulation	0.038-0.040	40	Low	-	M	W,F
Flax insulation	0.038-0.040	30-35	Low	-	M	W,F
Aerogel insulation	0.013	180	Low	+	M	W
Perlite	0.040-0.060	32-400	-	+	S,L	W,R,F
Cellular glass	0.037-0.050	100-200	High	+	S	W,R,F
Cork	0.038-0.050	105-120	Medium	-	S	W,R

* Typical values, examples may exist which go beyond stated values. Note that thermal conductivities quoted in references may vary due to slightly different measuring standards used; some indicate values as declared values or design values, others do not give reference to this distinction.

5. Construction requirements and costs

5.1 Key parameters in the incorporation of insulation materials

This section introduces the general principles in incorporation of insulation materials, and provides an overview of the key features of insulation materials in regard to these construction principles. The section is meant to put the following descriptions of each insulation material into perspective. The fire safety issues in relation to insulation materials are described in Chapter 6.

5.1.1 Insulation efficiency

Insulation capacity
The insulation capacity needed to secure the required temperature profile over a wall, roof or another building element is a key factor in the use of insulation materials. The insulation capacity required depends on the local needs in relation to outdoor temperatures, sun radiation, desired energy-efficiency of the building and related regulatory issues. The highest possible insulation capacity at the least cost and best technical suitability is however always pursued.

Thermal conductivity
The specific **thermal conductivity** of a material is one of the factors used to indicate insulation capacity. The thermal conductivity (k or λ) is specific for a homogenous material and it is an expression of the quantity of heat that passes in unit time through an area of 1 m^2 and a thickness of 1m when its opposite faces differ in temperature by one degree Kelvin. The thermal conductivity is measured in watts per meter Kelvin, W/(m·K). The thermal conductivity is temperature-dependent and thus needs to be measured under comparable conditions to enable comparison between insulation materials.

When comparing different insulation materials, as done below, it is relevant to compare solutions with a similar insulation capacity, taking the differences in the thermal conductivity of the materials into account.

The insulation capacity of a given homogenous insulation layer is termed the **thermal conductance** (C) and is defined as follows:

Thermal conductance, $C = \lambda * A/L$,

where λ is the thermal conductivity (specific for the material), A is the area and L is the thickness of the material.

The thickness needed to meet a desired thermal conductance can thus be calculated as

$L=\lambda$/Thermal conductance,

meaning that the thickness is linearly correlated with the (specific) thermal conductivity of the materials. In other words, when using an insulation material with two times the thermal conductivity as another insulation material, you need two times the thickness to obtain the same insulation capacity.

The thermal conductance has the unit $m^2 \cdot K/W$ and is the reciprocal of the thermal resistance (R-value) measured in $W/m^2 \cdot K$. Both parameters are widely used for description of the insulating capacity of an insulation material of a given thickness.

5.1.2 Gaps, compaction and compression

To maintain optimal insulation capacity, it is important to avoid gaps in the insulation material. Gaps can be caused by un-careful mounting of the material, or by inherent compacting and shrinkage of the material. Gaps in the insulation can severely reduce the overall efficiency of the insulation. Man-made gaps can be avoided by careful cutting and mounting of the insulation. Some insulation materials are designed to be flexible, as for example mineral wool or flax mats, making the material capable of expanding slightly after the mounting and thus closing gaps between mats or between mats and woodwork, etc. EPS and equivalently inflexible materials will have to be fit carefully together in the construction to avoid gaps. The use of multiple layers with alternating joints placement can reduce gaps between such boards on large surfaces such as floors, etc. Also boards with tongue and groove and similar joints reduce the risk of gaps.

Compacting of the insulation material with resulting gaps can occur over time after pouring or blowing in loose fill cavity insulation such as EPS beads, mineral wool or cellulose (/paper) insulation. This can be avoided by following careful procedures that ensure that the cavity is adequately filled up with insulation material from the beginning.

Some insulation materials may shrink a few percent over time, such as for example PUR/PIR boards, resulting in gaps between adjoining boards. Again the risk of gap formation can be reduced by using multiple layers or boards with tongue and groove.

Compression of the insulation material with reduced thickness and void formation as results can also reduce the insulation capacity as well as reduce the strength of the overall construction in which the insulation material take part. This can for example be the case in horizontal insulation applications such as flat roofs, where the insulation material supports the upper, watertight barrier. Compression here may lead to reduced insulation capacity and leaks in the water tight membrane and moisture damages of the building. Compressive strength is an important parameter for such applications, and data for this parameter is usually available for insulation materials suitable for horizontal applications designed for mechanical pressure.

Generally, detailed and comprehensible manuals for the optimal mounting of insulation materials are made available by insulation material manufactures on their web pages or as brochures.

5.1.3 Moisture resistance

Moisture in the insulation material reduces the insulation capacity. It may also cause severe damages to the building, due to the formation of rot and mould in the insulation material as well as in adjoining materials such as wooden rafters, joists, etc. Rot and mould may reduce the strength of bearing building materials and produces spores which can cause health effects in the indoor climate.

Moisture in the insulation material can be caused by condensation from damp air inside the insulation materials, by direct precipitation and by migration from adjoining, wet materials including from the ground, if not properly protected.

For these reasons, the insulation material is often protected from direct precipitation by façade boards, water resistive wind barriers or plasterboards, and separated from potentially wet foundation materials, etc. by a moisture barrier such as bitumen membrane, or similar. Some construction types do however not necessarily give this protection of the insulation material. This may for example be the case for façades with rendering applied directly on the insulation material and cavity insulation behind outer masonry, where rain may readily penetrate the masonry or rendering, if standard plaster is used. To avoid this, insulation material manufacturers often supply water tight rendering systems, which have the plaster appearance, but protects the insulation material better.

Avoiding condensation of water from damp air requires well designed control of air movements in the insulation accomplished by the use of vapour barriers on the warm side of the insulation (where the air is generally damper), by proper ventilation on the cold side to remove the moisture or by applying pressure or under-pressure to control air movements as appropriate.

Some insulation materials are inherently waterproof, for example cellular glass, or water resistant meaning that water may penetrate the insulation, but besides reducing the insulation capacity, it does no harm to the insulation material itself. The latter if for example the case for mineral wool, EPS, PIR/PUR, aerogel insulation, etc.

Raw materials for insulation which are not inherently waterproof or water resistant, such as wood insulation boards, flax and hemp may be treated with water repellents such as paraffin to reduce water uptake in the fibres and/or by biocides such as borax to prevent rot or mould formation in organic materials. The borax also acts as an inorganic fire retardant.

Dry storage of insulation materials on the building site is important to avoid the problems mentioned above. This can be secured by adequate packaging, care in handling of the materials, and by keeping storage time short.

5.1.4 Insulation in warm climates

Similar to insulation in cold climates, insulation used on humid tropical areas should be protected to absorb as little water as possible as the water negatively influences the thermal properties of the insulation materials and may lead to degradation. As mentioned, in warm climates the primarily influx of moisture comes from the outside of the façade wall, which should thus be sealed carefully with a vapour barrier.

Some insulation materials (PIR, EPS and perhaps more) have reflective surfaces or graphite particles incorporated which reflect some of the infrared radiation, especially relevant in hot climates. Reflective foils may also reduce the inward impact of heat radiation.

In warm climates like the Arabic Gulf, new buildings are often insulated with EPS or PUR/PIR insulation boards. Fire retardant and moisture resistant qualities are preferred due to the high temperatures and periodically moist conditions. In China, EPS, XPS, PUR, and phenolic foam are used for roofs, external walls, etc. Stone wool, aeroconcrete and other inorganic materials are also used. Authorities have announced that restrictions on the use of the combustible insulation materials may be on the way due to several fire accidents recently.

In warm climates, the use of heavy materials with high heat capacity has traditionally been the key technique to resist the heat and even out temperature changes between day and night.

5.1.5 Other degrading impacts

Some insects may feed from or live in natural fibre insulation materials. Borates are used in some such materials to prevent insect attach (as well as to provide mould protection and act as inorganic flame retardant).

5.1.6 Mounting of insulation

The key factors in the process of mounting of insulation materials are secure mounting, quick shaping and mounting for cost efficiency, possibilities for efficient dismantling during renovation or demolition work to secure optimal recycling possibilities and reduction of waste deposition fees, and securing an acceptable working environment.

The quick and efficient forming of the insulation materials into the shapes needed generally require knives or saws, in some cases special tools are supplied by the manufactures to enhance efficient shaping. Most of the insulation materials dealt with here are relatively light and porous materials and are thus relatively easy to shape, but the time and effort required may vary with the material. Some insulation materials require the use of personal protection to avoid health impacts of dust or fibres.

Fixation of the insulation material must be effective and quick. Recommended procedures are generally provided by the insulation material manufacturer. The fixation must be effective also during fire, as non-combustible insulation generally forms a part of the fire-retention of the building, and for the combustible insulation materials to avoid that they move and enhance the spreading of the fire. The means of fixation vary depending on materials and application. Often, the insulation material is encapsulated by other building materials (wind barriers, plasterboards, concrete, batters, etc.) on most or all sites, thus keeping it in place. In constructions where the insulation is ventilated or open on one or more sides, the insulation must be fixed to adjoining bearing building materials by steel wire (for soft materials), with screws with disks or wide heads or with glue. The producers of insulation material often supply fixation systems which may include glues, suitable screws, plastic plugs to reduce/eliminate cold bridges, and fixation profiles in metal which may also form a moisture barrier towards the foundation, or similar.

Glues may be quick to use for mounting but may prevent a quick and efficient separation of materials during renovation or demolition work.

5.1.7 Weight, size and handling

The weight and size of the insulation elements or packages are important for the mechanical workload and strain of the construction workers and also have consequences for transport in all life cycle stages off-site and for on-site mounting logistics. The density of the insulation materials described here varies between 16 and 240 Kg/m^3, with glass mineral wool being among the lightest and wood fibre insulation boards being among the heaviest. The density of the building material may influence the size of the individual boards, slaps or mats of insulation material, as each element should generally be manageable with manual labour. All the materials described here are however relatively light-weight compared to most other building materials. Usually insulation materials have low weight, as enclosed air in the material gives the insulating effect. As mentioned, EPS insulation has however a slightly increasing insulation efficiency with higher density in the normally used ranges. This is due to the fact that the air gets more tightly enclosed in the qualities with higher densities (up to a certain level; Byggforsk, 2004).

Material volume is also an issue in the transport and handling of insulation. Some light-weight insulation materials, for example glass mineral wool, can be compacted in their packaging and resume full volume after unpacking, and can thus save transport costs and storage space and make handling on the building site easier.

5.1.8 Working environment

Besides the mechanical work impacts mentioned above, dust, fibre and chemicals from several kinds of insulations may pose a risk in the working environment during the construction of a building, unless adequate precautions are taken. This issue is dealt with in section 8.

5.2 Assessment of alternatives in view of construction requirements

In the following sections the technical features of the selected alternatives to EPS are described, and prices are provides for applications similar to some of the key applications of EPS.

For the comparison, prices of the materials have been obtained for the German market. Flame retarded EPS is extensively used in Germany. At the same time Germany has a relatively mature market for all the considered insulation materials and the prices on this market is considered to reflect the real differences in the costs of manufacturing the materials. Prices are list prices (net prices excl. VAT) as indicated by the manufacturer's price lists. The price lists are mainly downloaded from a large German wholesale dealer of insulation materials May 2011.

Note that the actual prices may often be lower than the listed prices, and prices vary heavily with local market conditions and the prices and difference in price between the materials may be different in other countries.

5.2.1 EPS

For a description technical features and applications of EPS, please see Section 3.2.

Examples of products and their key data and prices are provided in Table 5.1. The prices of the EPS boards range from 11.6 EUR/m^2 to 17.9 EUR/m^2 at 100 mm thickness (Germany 2008/2009 – price lists downloaded May 2011). Prices indicated in the price lists from two manufacturers are very similar.

The prices are dependent on the thermal conductivity and the compressive strength of the boards. For boards used for the same application area, e.g. flat roofs, the price of an EPS 200 board is approximately 40% higher than the price of an EPS 100 board of the same thermal conductivity. The price increases by about 8% going from a board with a thermal conductivity of 0.040 W/(m·K) to a board of a thermal conductivity of 0.035 W/(m·K).

Table 5.1 Examples of EPS insulation board products and selected key data

Product		Application	Thickness, mm	Price at 100 mm* EUR/m^2	Thermal conductivity W/(m·K)	Compressive strength at 10%, kPa
1.1	Knauf Therm Wärmedämmplatte 040 DEO dm 100 *	Multipurpose, Indoor ceiling, wall, roof	20-200	12	0.040	100
1.2	Knauf Therm Wärmedämmplatte 035 DEO dm 100 *	Multipurpose Floor, ceiling	20-200	13	0.035	100
Knauf Therm Wärmedämmplatte 035 DEO dh 200 *		Multipurpose Floor, ceiling	20-200	18	0.035	200
Knauf Therm Fassadendämmplatte 040 WDV *		Outer wall for rendering	60-200	13	0.040	NA
Knauf Therm Fassadendämmplatte 035 WDV *		Outer wall for rendering	60-200	15	0.035	NA
Knauf X-Therm Fassadendämmplatte 035 *		Outer wall for rendering	60-200	15	0.035	NA
Knauf Therm Flachdachdämmplatte 035 dm 100 *		Flat roof	80-200	13	0.035	100
Knauf Therm Flachdachdämmplatte 035 dh 200 *		Flat roof	80-200	18	0.035	200
1.3	Schwenk, Flachdach dämmplatte, 035/DAA dm **	Flat roof	60-200	13	0.035	≥100
1.4	Schwenk, Flachdach dämmplatte, 035/DAA ds **	Flat roof	60-200	18	0.035	≥200

Notes: *: Recommended prices, Germany, 2008 (Knauf, 2011); ** Germany 2009 (Swenk, 2009). Both price lists are downloaded May 2011 and indicated as actual prices.

5.2.2 Stone wool

Applications

As shown in Section 4.2, stone wool is marketed for most of the building application areas where EPS is traditionally used, including in sandwich panels. The same is the case for glass wool, but stone wool is described here as an example from the group of insulation materials based on mineral wool.

For applications which require relatively high compressive strength, qualities are marketed which have a high-density, firm upper layer and a thicker layer with lower density and higher thermal resistance. Such qualities are marketed for flat roofs, outer wall façades for direct rendering, and other applications.

Insulation efficiency

The thermal conductivity of stone wool is the similar to or slightly higher than EPS, meaning that the insulation efficiency of stone wool is similar to or slightly lower than EPS.

Moisture resistance

Stone wool is not in itself sensitive to moisture. While in some qualities of stone wool, the fibres are water repellent, stone wool is an open, wool-like material and does thus allow the penetration of water. Once trapped in or behind the insulation, the water can however evaporate out through the insulation again if the insulation is ventilated on the cold side, and it will thus not prevent moisture accumulated on adjacent building materials from being vented (like water-tight materials like EPS and PUR/PIR could potentially do if not mounted and vented properly).

Dimensional stability, compacting and shrinkage

Stone wool is available in qualities with compressive strengths in the range of 20-80 kPA (GDI, 2007). The most compact types have a compressive strength similar to the compressive strength of EPS in the EPS 60-100 range, which are the most widely used types. The compressive strength of stone wool cannot match the compressive strength of EPS types with higher strength than EPS 100. The stone wool keeps its form and flexibility in its lifetime, if used and worn as prescribed. Softer stone wool qualities should be mounted and used properly to avoid compacting them unintentionally and thus leaving gaps with reduced insulation efficiency. On the other hand, the elasticity of the softer qualities of stone wool allows them to be fit and fixed tight into the construction very quickly in the mounting situation; a quality which the stiffer insulation materials such as EPS, PUR and cellular glass do not have.

Prices

Price examples for stone wool insulation batts are shown in Table 5.2. The lowest price is for cavity wall insulation where the price is lower than the price of EPS boards. The price is even lower for slaps for insulation of lofts and pinched roofs and for these applications stone wool and other mineral wool are highly competitive and in many countries the material of choice.

For the key applications of EPS considered here, such as flat roofs, floors and outer façades the prices of the stone wool are higher than the price of the EPS boards. Prices vary much depending on application and quality of the products. For flat roofs e.g. the prices range from 22 to 40 EUR/m^2, but the most expensive products with fibre reinforced coating are not readily comparable with the EPS. The prices for stone wool batts for the applications concerned are typically 10-30% higher than for EPS.

For sandwich panels, particular stone wool products optimised for sandwich panels product lines are manufactured e.g. the Spanrock, Conrock and Lamrock from Rockwool (Rockwool 2011f). Prices have not been available.

Table 5.2 Examples of stone wool insulation slaps and selected key data

Product (Rockwool)	Application	Thickness mm	Price at 100 mm* EUR/m^2	Thermal conductivity W/(m·K)	Compressive strength at 10% kPa
Fixrock 035 *	External walls, behind ventilated cover	60-240	16	0.035	not indicated
Coverrock 035 ***	Outer wall with rendering	60-180	20	0.036	≥5
Flexirock 040 *	Cavity wall insulation	80-200	10	0.035	not indicated
Floorrock AP ***	Pressure-resistant rock wool insulation for thermal insulation under floating floors.	20-160		0.040	≥ 60
Megarock **	Flat roof- Roof insulation panel with upper, inorganic, fiber-reinforced coating.	60-160	40	0.042	≥ 80
Hardrock II **	Pressure-duty board with integrated two-layer characteristics and high-density top layer.	50-140	25	0.040	≥ 70
Durock 040**	With integrated two-layer characteristics and high compacted top layer.	60-180	22	0.037	≥ 60
Stone mineral wool (Rockwool RockBase façade batts ****	Outer wall with rendering	80-250	20	0.037	not indicated

* Prices Germany 2011 from Rockwool, 2011a; ** Rockwool , 2011b; *** Rockwool, 2011c; ****Rockwool, 2011e (Danish price 2011)

5.2.3 Polyurethane foam (PUR/PIR)

Applications

The PUR/PIR foam sheets are marketed for most of the same applications in buildings as the EPS as described in section 4.4. including in sandwich panels. The PUR/PIR foams share some of the key properties with the EPS as regard low density and relatively good water resistance. For this reason the PUR/PIR foams are applicable for most of the applications where EPS has a significant market share.

PUR/PIR insulation offers a relatively high compressive strength at low weight. The rigid PUR/PIR foams are manufactured in a range of densities for different application areas. Foams used in building normally ranges between 30 kg/m^3 and 45 kg/m^3, however it can reach 100 kg/m^3 for some applications. As for the EPS, the properties of the PUR/PIR foams depends on the density of the foams, but are also dependent on the blowing agent (cell gas) used.

Insulation efficiency

The insulation efficiency of PUR/PIR insulation boards is on average somewhat higher then that of EPS. The thermal conductivity of PUR/PIR is reported to be in the interval of 0.022-0.028 W/(m*K), meaning that the higher value for PUR/PIR is around the lower value for EPS boards. This means that the same insulation capacity can be obtained with thinner dimensions.

Moisture resistance

The closed cell structure prevents water penetration and makes the insulation capacity largely unaffected by air movement or moisture.

Dimensional stability, compacting and shrinkage

PUR/PIR foams have high dimensional stability, but minor shrinkage of panels have been reported which can lead to gaps in the insulation layer with reduced insulation effectiveness (Greenspec, 201; Byggforsk, 2004). Jointing of panels (e.g. tongue & groove) and multiple layers can however reduce this problem.

Table 5.3 Examples of PUR/PIR insulation boards and selected key data

Product	Application	Thickness mm	Price at 100 mm* EUR/m^2	Thermal conductivity W/(m·K) **	Compressive strength at 10%, kPa **
ECOTHERM® SlimLine KD 024	Cavity wall insulation	60-100	25	0.023	not indicated
PIR board (Kingspan Thermawall TW55)	External walls in timber and steel frames	25-65		0.022	>140
PIR (Kingspan Thermawall TW53)	External insulation for masonry walls)	20-100		0.028	>150
ECOTHERM® BaseLine MG	Floors. For insulating basement ceilings, floors and upper floors - with mineral-sided fleece lining	30-100	23	0.028	100
ECOTHERM® BaseLine XR	Floors. For insulating basement ceilings, floors and upper floors – with aluminium sided multilayer coat	20-80	25	0.024	not indicated
ECOTHERM® TopLine XR	Flat roof. A PIR rigid foam insulation board with an aluminium multi-layer complex on both sides for thermal insulation and drainage of flat roofs.	60-180	24	0.023	>120 at > 80 mm
ECOTHERM® TopLine MG	Flat roof. A PIR rigid foam insulation board with a mineral glass fibre on both sides for thermal insulation of flat and moderately pitched roofs.	60-180	22	0.026	>120 at > 80 mm

*Prices Germany 2010 from Ecotherm, 2010. ** Technical description from Ecotherm, 2011.

Prices

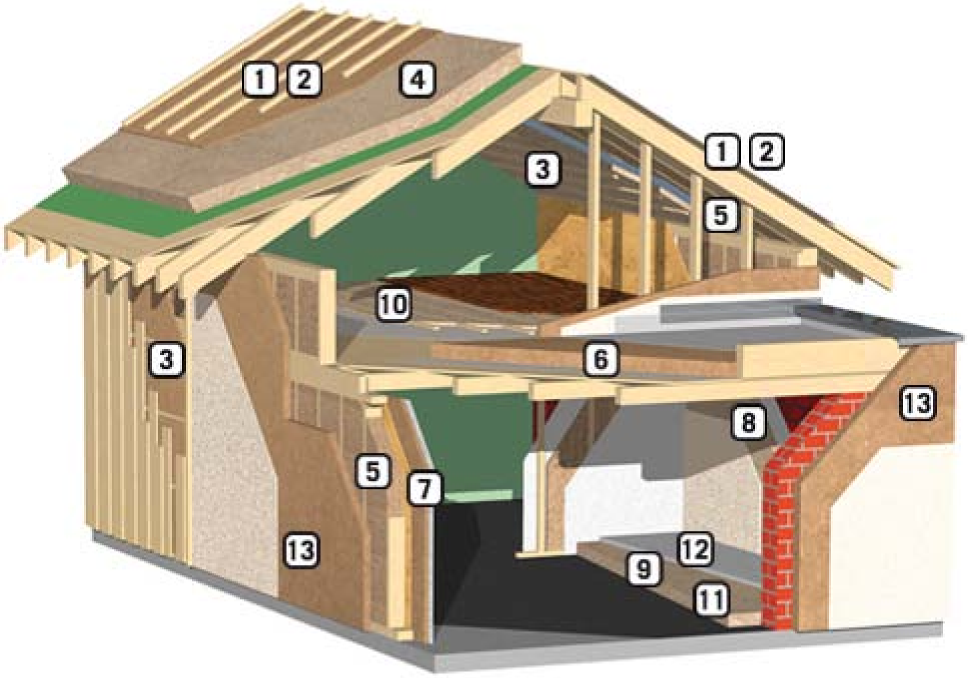
Prices vary much depending on application. Examples of prices of PUR/PIR boards are shown in Table 5.3. Prices of flat roof insulation boards are shown for the cheapest in the product range. More expensive boards for particular applications are marketed. These boards are not readily comparable with the EPS as the products are typically coated. Considering the lower thermal conductivity (and thus lower thickness), the price of the cheapest PUR/PIR insulation boards is typically 10-30% higher than EPS for similar applications.

5.2.4 Wood fibre insulation board

Applications

Wood fibre insulation board are marketed for use in most of the normal building application areas where EPS is used (Gutex, 2011; Pavatex, 2011). Sandwich panels with wood fibre insulation and other organic insulation and construction materials are marketed, but outer wall and roof insulated steel panels have not been observed . Qualities are available from several producers with adequate compressive strengths for flat roof applications, rendered outer walls, floors, etc. An indication of the full array of applications is given in Figure 5.1

Figure 5.1 Applications for wood fibre insulation boards. The numbers indicate different product qualities adapted for the applications (Gutex, 2011).



Insulation efficiency

The insulation efficiency of wood fibre insulation boards is on average somewhat lower than that of EPS. The thermal conductivity of wood fibre boards is reported to be generally in the interval of 0.037-0.050 W/(m*K), meaning that the lower value for wood fibre insulation board is around the higher value for EPS boards. This means that a thicker layer is needed to obtain the same insulation effect as for EPS.

Moisture resistance

The wood fibre insulation board products assessed are resistant to short time water saturation and can tolerate a continuous moisture concentration in the fibres up to 20%. According to a producer, this is fully adequate in normal situations in temperate climates (Gutex, 2011b), where the insulation is protected carefully against direct exposure to moisture and towards vapour from the air. As a natural fibre, wood is however subject to rot and degradation if continuously exposed to water and excessive moisture. This means that moisture control is of major importance. Manufacturers have systems to enhance proper moisture control. For example for outer walls with rendering applied directly on the insulation board, Gutex has a custom-made water tight rendering system and special profiles which provide fixation and at the same time acts a moisture barrier towards the potentially wet foundation. This system is categorised as "WAP", meaning insulation systems for outer walls with rendering in the German application norm for insulation materials DIN 4108-10, which governs the application of insulation materials in the large and for insulation materials relatively diverse German market (Baumarkt.de, 2011). Gutex does not know of practical experience with the use if wood fibre insulation boards in wet, tropical conditions (Gutex, 2011b).

Wood fibre insulation board is a diffusion-open material, and therefore accumulated moisture can evaporate from the insulation material if the cold side of the insulation is vented, and it will thus not prevent moisture accumulated on adjacent building materials from being vented (like water-tight materials like EPS and PUR/PIR could potentially do if not mounted and vented properly).

Also in flat roof constructions, wood fibre insulation board must be kept dry to maintain its characteristics and avoid rot and mould. In practise, this may be one of the more challenging applications to meet for this material.

Table 5.4 Examples of wood fibre insulation board products and selected key data

Product (Gutex)	Applications	Thickness, mm	Price at 100 mm EUR/m^2	Thermal conductivity, W/(m·K)	Density kg/m^3	Compressive strength kPa
Gutex, Thermosafe Homogen *	Board w. tongue and groove for multiple purposes	40-240	20	0.040	<110	>=40
Gutex, Thermoflex *	Soft, flexible board for cavity insulation	40-240	13	0.037	45	not indicated
Pavatex, PAVAFLEX**	Flexible external wall insulation	40-240	13	0.039	55	not indicated
Gutex, Thermoflat *	Board w. tongue and groove for flat roofs	100-160	27	0.042	140	>=70
Gutex, Thermowall *	Board w. tongue and groove for walls - Outer wall with rendering	100-160	35	0.042	160	≥ 100
Pavatex DIFFUTHERM**	Outer wall with rendering	100-200	35	0.043	190	not indicated
Gutex, Thermosafe-nf *	Floors under floating floors	41	28	0.039	<160	not indicated
Gutex, Ultratherm *	Rain resistant board w. tongue and groove for pitched roofs	50-100	29	0.045	180	>=150

* Prices Germany 2011 from Gutex (2011); ** Prices Germany 2011 from Pavatex (2011b)

Weight

Wood fibre insulation board is, along with cellular glass, the heaviest insulation materials included in this study. With densities between some 110-240 kg/m^3, the densest boards may imply the usage of higher dimensions of concrete or timber for roofs and similar. Normally, other forces like the weight from humans and material placed on the roof, wind powers and precipitation are important factors in the dimensioning of a house. However, the weight may influence the logistics in the building process.

Dimensional stability, compacting and shrinkage

Wood fibre insulation board is dimensionally stable and is available as both flexible and compacting resistant qualities.

Prices

Prices of wood fibre boards vary much depending on application however (Gutex, 2011; Pavatex, 2011). Some examples of products and their key data are provided in Table 5.4. The price for the cheapest flexible boards for cavity insulation is approximately the same as for EPS, but for the applications concerned, the price is typically (when the higher thermal conductivity is considered) 50-100% higher than the price of EPS.

5.2.5 Cellular glass

Applications

- Cellular glass is an insulation material with very high compressive strength and due to its water tightness it is also a capillary barrier. Its compressive strength is considerably higher than EPS or any other insulation materials described in detail in this study. This means that it may give most value for money in the applications where this quality is important, especially for flat roofs with roof terraces, vehicle traffic or other high compression applications. It is however also marketed for most other traditional EPS applications such as external façades, floors, inner walls, etc.
- An example of the usage of cellular glass insulation in a façade with rendering is shown in Table5.5. "PC® 56" glue is a plasticised, solvent-free dual-component glue based on mainly bitumen and cement components (Foamglas, 2011b). Cellular glass is available as blocks and boards, and may be glued or screwed to adjoining materials.

Table 5.5 Cellular glass ("Foamglas®") in a façade with rendering (Foamglas, 2011a)

Insulation efficiency

The insulation efficiency of cellular glass is on average somewhat lower then that of EPS. The thermal conductivity of cellular glass is reported to be generally in the interval of 0.037-0.05 W/(m*K), meaning that the lower value for wood fibre insulation board is around the higher values for EPS boards. The applications of cellular glass with the lowest density (and highest insulation efficiency) however corresponds to the applications of high-density EPS, stone wool, etc., so in a comparison, the difference for the same application is smaller than indicated by the numbers mentioned.

Moisture resistance

Cellular glass is a chemically inert, water tight material which cannot rot. For floors with ground contact, the cellular glass provides high efficiency insulation and capillary barrier in one material. Cellular glass can form water tight barriers when glued with specialised glue for the purpose. As such, cellular glass can used as insulation for floors, foundations and cellars in direct contact with the ground, also with constant water pressure, and, depending on the specific construction features, as load bearing construction material (Foamglas, 2011c).

Weight

Cellular glass insulation is, along with wood fibre insulation board, the heaviest insulation materials included in this study. With densities between some 100-200 kg/m3, the densest boards may imply the usage of higher dimensions of concrete or timber, etc. for roofs and similar. Normally, other forces like the weight from humans and material placed on the roof, wind powers and precipitation are important factors in the dimensioning of a house. However, the weight may influence the logistics in the building process, if the material is used above ground level.

On the other hand, cellular glass can be used as a load bearing material, it can be mounted air-tight and with no need for intermittent ventilation to the outer cladding of a building, and thus save space and potentially reduce dimensions of adjoining materials (Foamglas, 2011a).

Dimensional stability, compacting and shrinkage

Cellular glass has a high and lasting dimensional stability and can even be used as a load bearing construction material.

Prices

Cellular glass is currently in the high end compared to prices for traditional insulation materials such as for example EPS and stone wool. But its qualities are also closer to the more expensive EPS qualities for high strain applications. In North European settings it seems so far mainly to have been used where its key characteristics have been most appreciated such as flat roofs with high loads, ground contact, high end or structurally demanding building, as well as green building.

Examples of products and their key data are shown in Table 5.6. The prices are in general more than twice the price of EPS boards.

Table 5.6 Examples of cellular glass insulation products and selected key data ((Foamglas, 2011a; ZES, 2011).

Product examples	Applications	Thickness provided mm	Price at 100 mm EUR/m^2 *1	Thermal conductivity, W/(m·K)	Density kg/m^3	Compressive strength at 10% kPa
Foamglas T4+ (blocks/boards)	Façades, bearing walls, floors, flat roofs, roofs, ceilings	30-180	44	0.041	115	400
Foamglas s3 (blocks/boards)	Flat roofs and floors for very high pressures	40-160	47	0.044	135	600
Foamglas f (blocks/boards)	Flat roofs and floors for driving on, etc.	40-150	61	0.050	165	900
ZES cellular glass, ZES800 (among several types)	High compression applications		27 (China)	0.043	120	800

Notes: Germany 2011 net prices (excl VAT) (Foamglas, 2011e) and China (ZES, 2011) Technical data provided by producers' technical data sheets.

5.3 Prices of insulation materials

Prices of the materials have, as already mentioned, been obtained for the German market. In order to compare prices of insulation materials for the same applications, the materials and prices presented above are in this section organised by application. In order to compare prices it is relevant to compare materials with the same insulation capacity defined by the thermal resistance of the material at a given thickness. All the prices are therefore normalised to a thermal resistance of 2.857 m^2·K/W corresponding to 10 cm insulation at a thermal conductivity 0.035 W/(m*K) like a typical EPs board. This thermal resistance is identical to the resistance of the "functional unit" used for life cycle assessment (LCA) in Chapter 7. For materials with a thermal conductivity lower than 0.035 W/(m*K) less than 10 cm is needed, and visa versa for materials with a higher conductivity. The definition of thermal conductivity used by producers may vary slightly, and may also be dependent on the thickness of the boards, introducing a minor uncertainty into the comparisons. For those materials where different thermal conductivities are indicated in technical data sheets, the value for a sheet of 100 mm is applied.

External façade insulation

Price comparison for external wall insulation is indicated in Table 5.8 below. For some of the alternative materials the price is higher if insulation materials is use as basis for a rendering as compared to materials used behind a cover e.g. of metal sheets. For stone wool insulation to be used behind a cover, the price is comparable or slightly higher than the price of EPS, whereas the prices for boards used for rendering are higher.

It should be noted that differences in prices for entire insulated rendering systems (including insulation, plaster, binders, etc.) have not been compared.

Table 5.7 Examples of prices and key technical data for selected products suitable for external façade insulation (sources of information: see tables above)

Parameter	Applications	Thermal conductivity, λ*1	Nominal density	Price at 100 mm	Price at functional unit *	Thickness at functional unit *
Unit	-	W/(m*K)	kg/m³	EUR/m^2	EUR/m^2	cm
EPS board (Knauf Therm Fassadendämmplatte 035)	Outer wall, etc.	0.035	22.9	15	15	10
Wood fibre insulation board, (Pavatex DIFFUTHERM)	Outer wall with rendering	0.043	190	35	43	12
Wood fibre board (Gutex Thermowall)	Outer wall with rendering	0.042	160	36	43	12
PIR board (Kingspan Thermawall TW55)	External walls in timber and steel frames	0.022	32			6
PIR (Kingspan Thermawall TW53)	External insulation for masonry walls	0.028	32			8
Cellular glass (Foamglas wall board T4+)	Façades, bearing walls, floors, flat roofs, roofs, ceilings	0.041	115	44	52	12
Stone mineral wool (Rockwool Fixrock 035)	External walls, behind cover	0.035	52.5	16	16	10
Glasswool, Superglass, fassadendämmplatte fp 2/v – 035	External walls, behind cover	0.035	-	16	16	10
Stone mineral wool, (Rockwool Coverrock,)	Outer wall with rendering	0.036	100.5	20	21	10
Stone mineral wool (Rockwool RockBase façade batts)	Outer wall with rendering	0.037	105	20	21	11

* Functional unit: insulation needed for thermal resistance of 2.857 m^2·K/W corresponding to 10 cm insulation at a thermal conductivity of 0.035 W/(m*K).

Flat roof

Price comparison for flat roof insulation is indicated in Table 5.8. The prices will be very dependent on the actual load of the roofs, the covering and other factors. Horizontal roofs often have a load bearing structure of concrete or metal with insulation above the deck (so-called warm roofs). In most cases a vapour barrier, placed directly above the concrete or metal deck or between layers of insulation, is needed. The insulation is covered by a water tight roofing membrane, which can be of different kinds.

If mineral wool is applied it is of relatively high density and may be reinforces. Cellular glass are used for some applications with high load e.g. roof gardens. For illustration also prices for XPS, widely used for this application, are indicated. The price of the XPS is higher than the price of EPS and at the same level as mineral wool. The lowest prices of the PUR/PIR products (the cheapest in the PIR/PIR product range) are in between the prices for EPS 100 and EPS 200, whereas prices for cellular glass are significantly higher. The cellular glass also has much higher compressive strength and is applied for applications with high loads.

Table 5.8 Examples of prices and key technical data for selected products suitable for flat roof insulation (sources of information: see tables above unless otherwise indicated)

Parameter	Applications	Thermal conductivity, λ*1	Compressive strength at 10%,	Price at 100 mm	Price at functional unit *	Thickness at functional unit *
Unit	-	W/(m*K)	kPa	EUR/m²	EUR/m²	cm
EPS,Knauf Flachdachdämmplatte 035 dm 100	Flat roof	0.035	100	13	13	10
EPS. Knauf Therm Flachdachdämmplatte 035 dh 200	Flat roof and perimeter insulation	0.035	200	18	18	10
XPS, DOW ROOFMATETM SL-A **	Flat roof , top roof car parks, roof gardens	0.036	300	23	24	10
XPS, DOW ROOFMATETM SL-X **	Flat roof , top roof car parks, roof gardens	0.029	300	27	22	8
Mineral wool Megarock **	Flat roof- roof insulation panel with upper, inorganic, fiber-reinforced coating.	0.042	≥ 80	40	48	12
Mineral wool Hardrock II **	Pressure-duty board with integrated two-layer characteristics and high-density top layer.	0.040	≥ 70	25	29	11
Mineral wool Durock 040**	With integrated two-layer characteristics and high compacted top layer.	0.037	≥ 60	22	23	11
PUR/PIR, ECOTHERM® TopLine XR	A PIR rigid foam insulation board with an aluminium multi-layer complex on both sides for thermal insulation and drainage of flat roofs.	0.023	>120 at > 80 mm	24	16	7
PUR/PIR, ECOTHERM® TopLine MG	A PIR rigid foam insulation board with a mineral glass fibre on both sides for thermal insulation of flat and moderately pitched roofs.	0.026	>120 at > 80 mm	22	16	7
Cellular glass Foamglas s3 (blocks/boards)	Flat roofs and floors for very high pressures	0.044	600	47	59	13
Cellular glass Foamglas f (blocks/boards)	Flat roofs and floors for driving on, etc.	0.050	900	61	87	14

* Functional unit: insulation needed for thermal resistance of 2.857 m²·K/W corresponding to 10 cm insulation at a thermal conductivity 0.035 W/(m*K).

** Prices Germany 2010 and technical data form Dow, 2010.

Floor insulation

Price comparison for floor insulation is indicated in Table 5.9 below. The prices will be very dependent on the actual load of the floors, the covering, and other factors. XPS is often used for floors and for illustration also prices for XPS of a compressive strength of 200 kPA are shown. They are slightly higher than the price of EPS with the same compressive strength. XPS with higher compressive strength are available at higher prices.

The prices of the PUR/PIR are at same level as the EPS 200, but higher than the price of EPS 100. The prices of wood fibre boards and the cellular glass are significantly higher. The products are not readily comparable as some products are mainly applied under floors with relatively low weight (e.g. below floating wood floors) whereas others are for floors with heavy weight. All alternatives are more expensive than the cheapest EPS 100.

Table 5.9 Examples of prices and key technical data for selected e products suitable floor insulation (sources of information: see tables above unless otherwise indicated)

Parameter Unit	Applications -	Thermal conductivity, λ*1 W/(m*K)	Compressive strength at 10%, kPa	Price at 100 mm EUR/m²	Price at functional unit * EUR/m²	Thickness at functional unit * cm
atte 035	Multipurpose Floor, ceiling	0.035	100	13	13	10
Knauf Therm Wärmedämmplatte 035 DEO dh 200	Multipurpose Floor, ceiling	0.035	200	18	18	10
XPS, DOW FLOORMATE™ 200-A *	Floors	0.035	200	20	20	10
Mineral wool Floorrock AP	Pressure-resistant rock wool insulation for thermal insulation under floating floors.	0.040	≥ 60			11
PUR/PIR ECOTHERM® BaseLine MG	Floors. For insulating basement ceilings, floors and upper floors - with mineral-sided fleece lining	0.028	100	23	18	8
PUR/PIR ECOTHERM® BaseLine XR	Floors. For insulating basement ceilings, floors and upper floors – with aluminium sided multilayer coat	0.024	not indicated	25	17	7
Wood fibre boards Gutex, Thermosafe-nf	Floors under floating floors	0.039	not indicated	28	31	11
Foamglas T4+ (blocks/boards)	Façades, bearing walls, floors, flat roofs, roofs, ceilings	0.041	400	44	52	12
Foamglas f (blocks/boards)	Flat roofs and floors for driving on, etc.	0.050	900	61	87	14

* Functional unit: insulation needed for thermal resistance of 2.857 m²·K/W corresponding to 10 cm insulation at a thermal conductivity 0.035 W/(m*K).

** Prices Germany 2010 and technical data from Dow, 2010

5.4 Summary of technical features and price levels

Table 5.10 below presents a summary of the technical feasibility and relative cost levels for the described alternatives to flame retarded EPS. The summary is based on the descriptions of the individual insulation materials and the prices provided above. Note that the price comparison concern the key applications of EPS included in the assessment. For cavity wall, loft and pitched roof insulation the mineral wools are typically the same price or less expensive than EPS.

Table 5.10 below presents a summary of the technical feasibility and relative cost levels for the described alternatives to flame retarded EPS. The summary is based on the descriptions of the individual insulation materials in this chapter.

Table 5.10 Summary of technical feasibility and cost of assessed insulation materials.

Technical solution	Technical feasibility		Price of functional unit compared to EPS*1,2
	Advantages (as compared to EPS)	Disadvantages (as compared to EPS)	
Stone wool	Diffusion-open, allows vapour to pass. Easier to fasten tight in some cases due to flexibility.	Similar to or slightly lower insulation efficiency. Higher weight. Lover compressive strength than some EPS types	≈/+
PIR/PUR	Significantly higher insulation efficiency. Higher compressive strength for some types		≈/++
Wood fibre insulation board	Diffusion-open, allows vapour to pass.	Slightly lower insulation efficiency. Somewhat vulnerable to moisture. Moisture may reduce insulation efficiency more than for EPS. Some qualities relatively heavy - may in some cases warrant stronger dimensions of load bearing structures.	+/++
Cellular glass	Much higher resistance to compression. Can be used as load-bearing material and can thus reduce dimensions of load bearing insulated walls in some cases. Insensitive to moisture and other climate and chemical pressures.	Slightly lower insulation efficiency. Higher weight - if used for decks, roofs etc., it may in some cases warrant stronger dimensions of load bearing structures, but it is most used where other forces dictate dimensions.	++

Notes: *1: ≈ prices similar to EPS;; + 10-30% more than for EPS; ++ >30% more than EPS *2: Functional unit: Insulation thickness which provides the same thermal resistance as 10 centimetres of EPS covered outer wall insulation.

6. Fire safety

The primary goal of fire protection is to limit, to acceptable levels, the probability of death, injury and property loss in an unwanted fire. The balance between life safety and property protection varies in different countries, depending on the type of the building and its occupancy.

In the first phase of fire development, heating of potential fuel is taking place. Ignition is the start of flaming combustion, marking the transition to the growth phase. In the growth phase, most fires spread slowly at first on combustible surfaces, then more rapidly as the fire grows, providing radiant feedback from flames and hot gases to other fuel items into the burning period. If the temperature reaches about 600 °C, the burning rate increases rapidly, leading to flashover. The rate of burning in the growth phase is generally controlled by the nature of the burning fuel surfaces. At flashover the temperature and radiant heat flux inside the room or inside the construction are so high that all exposed surfaces are burning and the rate of heat release is usually controlled by the ventilation.

The heat produced by burning material is one of the factors determining how a fire develops. The contribution to the production of smoke and toxic gases depends upon the nature of the material and how it is incorporated in the total construction.

The use of insulation in buildings based upon plastic foams and other combustible materials, both in interior or exterior constructions, might present a risk regarding to fire spread and production of smoke and toxic gases. Properties such as flammability, heat release, flame spread, smoke production and production of toxic gases will depend on the type of material and how the insulation is put together or used in the construction. Another important feature is whether the insulation melts, shrinks or chars when heated. Melting and shrinkage in a construction might create channels that will increase access to air, and then lead to a faster fire development inside the construction, and increase the risk of spread of fire inside the building or in the façade.

6.1 International building fire safety regulation relevant for EPS

Fire safety requirements of building insulation materials are described in national building regulations. Building fire regulations relate both to 1) fire resistance of construction and building element with a fire separating function and 2) the reaction-to-fire of a product. As flame retarded EPS is generally not used for building elements with a fire separating function, the following description focuses on the reaction-to-fire.

The reaction-to-fire of a product or building element deals with characteristics such as ignition, flame spread, heat release rate, smoke and gas production, and the occurrence of burning droplets and particles.

International building fire safety regulation relevant for the use of EPS/XPS insulation materials have recently been reviewed by Blomqvist *et al.* (2010). In Europe, the overlying EU regulations unify the method for testing EPS/XPS products in building applications, but the specific performance requirements differ significantly in the different EU Member States. In some Member States e.g. Sweden and Norway, only the performance of the final product (or building element) is tested, and the use of EPS/XPS as insulation material does not result in a formal requirement that the EPS/XPS used is flame retarded if the total building element meets the requirements. In other Member States, material performance is required, e.g. in Germany and Denmark, and in these countries EPS/XPS used for building insulation must be flame retarded in order to meet the required fire class. Besides the fire safety regulation, requirements from insurance companies may also govern the use of flame retarded grades, and UK is an example of a country where requirements from insurance companies has resulted in that the majority of EPS/XPS is flame retarded. It is noted by Troitzsch (2008) that the use of flame retarded EPS/XPS foams is compulsory in the majority of the EU and EFTA Member States for meeting the respective national fire safety levels.

According to the assessment by Blomqvist *et al*. (2010), in the USA and Canada, it seems that there are material requirements for insulation materials and as result flame retarded EPS/XPS would be most common in building applications. In Australia there are very low formal requirements concerning fire performance of materials, which would not necessarily require the use of flame retarded EPS/XPS, but verbal information received by the authors indicates that EPS/XPS generally used in Australia in building applications is flame retarded voluntarily. In Japan, it would appear that EPS/XPS would need to be classified as flame retardant material as it would not be able to attain any of the other classes without the use of flame retardants. This implies also that the majority of EPS/XPS for use in Japan would be expected to be flame retarded. Korea appears to have a similar situation as Japan.

For those countries where material performance of the insulation material itself is required by the regulation, it would typically not be an option to replace flame retarded EPS with non-flame retarded grades even if the construction is changed by use of thermal barrier materials. In those countries, the alternative would need to be another insulation material with the same fire properties as flame retarded EPS or better, unless the building regulation is changed. For the comparison of the insulation materials, the European classification system for building material's reaction-to-fire is applied in the next section.

For those countries where the use of flame retarded EPS is not governed by material performance requirements, replacing flame retarded EPS with non-flame retarded EPS is an option if the requirements for the fire performance of the building element as a whole can be met by use of fire resistant construction. Experience with use of non-flame retarded EPS and thermal barriers are described in section 6.3.

6.2 Reaction to fire

Classification of EPS and alternatives

Different classification systems for insulation materials exist in different countries. For convenience the Euroclass system applied in the EU and EFTA countries is in this report used for the comparison of the building insulation materials.

The European fire classification of construction products (EN 13501-1) classifies material products into seven classes using test data from reaction to fire in a range of fire tests. The test concerns temperature rise, mass loss, gross calorific potential, smoke growth rate, etc. Based on the tests, the products are grouped into seven Euroclasses ranging from A1, applying to non-combustible materials, to F, applying to materials with no performance determined. Additional sub-classes apply to smoke development and the occurrence of burning droplets. The Euroclasses along with an indicative performance description and examples of insulation materials are shown in the table below.

The Euroclasses apply to marketed products to be used in buildings; it may either be materials or building elements. The examples in Table 6.1 concern the uncovered insulation materials.

Of the assessed alternatives, flame retarded EPS would typically be classified Euroclass E, together with e.g. flame retarded wood fibre boards. Mineral wool insulation materials and mineral materials such as cellular glass or expanded clay is in Euroclass A1 or A2.

Non-flame retarded EPS cannot meet the requirements of Euroclass E or better and is classified in the Euroclass F, no performance determined. The addition of the flame retardant makes the EPS less combustible. The soften temperature of 100 °C is the same for both grades, but the addition of the flame retardant increase the ignition temperature with pilot flame from 350°C to 370°C and the self ignition temperature from 450°C to 500°C (BPF, date not indicated). The flame retarded grades have a tendency to shrink away from the heat source and the probability of ignition of the material is significantly reduced.

If build into a building element, e.g. a sandwich façade element, the Euroclass of the element may be higher than the class of the insulation material in itself. In building elements such as sandwich panels where the EPS is not exposed during the fire test, higher performance can be obtained (corresponding to class D, C and B) if the EPS insulation is sufficiently well protected from the fire. The higher classes can even be reached by elements where the EPS has not been flame retarded due to the protection given by the encapsulating materials.

Table 6.1 Euroclasses of selected insulation materials

Euroclass	Indicative performance description	Subclasses (smoke and flaming droplets) *1	Examples of insulation materials (uncovered)
A1	Non-combustible. (No contributions to the fire)	--	Foamglass Expanded concrete Expanded clay Stone wool (some)
A2	Non-combustible (Allows a very small contribution to the fire)	s1,s2,s3 d0, d1, d2	Stone wool (some) Glass wool (some)
B	Limited combustible (No flashover during test period of 20 minutes, 10 minutes with 100 kW and 10 min with 300 kW)	s1,s2,s3 d0, d1, d2	
C	Combustible (Allows more rapidly fire growth and higher total heat release. Not flashover for the 100 kW load for 10 minutes, but can cause flashover at 300 kW load.)	s1,s2,s3 d0, d1, d2	
D	Combustible (Allows even more rapidly fire growth. Not flashover for the 100 kW load for 2 minutes.)	s1,s2,s3 d0, d1, d2	Flame retarded PIR Flame retarded PUR (some)
E	Combustible (Measures only flame spread. Flashover within 2 minutes with 100 kW load.)	s1,s2,s3 d0, d1, d2	Flame retardant EPS Flame retarded PUR (some) Flame retarded wood fibre boards
F	No performance determined	--	Non-flame retarded EPS Non-flame retarded wood fibre boards

Subclasses:

s1 Low smoke production; s2 Medium smoke production; s3 High smoke production/no requirements.

d0 No flaming droplets; d1 Flaming droplets that persist for less than 10 s; d2 Flaming droplets/no requirements.

Formation of burning droplets

Most types of thermoplastics would, in addition to smoke, produce burning droplets. For materials and surfaces that are classified according to EN 13501-1, there are three classes of smoke: s1, s2 and s3, where s1 means least smoke, and three classes for droplet formation: d0, d1 and d2, where d0 means no droplet formation. Improvement of fire behaviour properties can be made by mixing of different additives. Some additives will have flame-retardant effect, while others can reduce the smoke.

Full-scale tests of plastic materials will require classification criteria for both smoke and droplet formation.

If EPS is exposed to temperatures above 100° C, it begins to soften and will then starts to melt. Burning of EPS would develop burning droplets which can spread a fire through the melted material.

PUR and PIR are thermosetting plastics and when heated they form a char, but do not melt. There will be no burning droplets. The char layer on the surface is porous, has low density, and will act as an insulating layer to protect the underlying material against exposure to heat and radiation from a fire. A smoldering fire will still be able to develop in this char layer.

Production of smoke

Smoke is defined as visible suspension of solid or liquid particles in the gas caused by combustion or pyrolysis (Drysdale 1998). Production of smoke is described as a secondary feature of the material, and limitation of smoke production can occur for example by improving the characteristics of ignitability, flame spread and heat release. By preventing that a material ignites and burns, the smoke production is similarly prevented significantly (SINTEF, 2001).

EPS produces smoke much more rapidly than insulation based for example upon mineral wool. If the surface area of the EPS insulation is large and unprotected, most of the smoke produced in the fire may be caused by the insulation. If the insulation is protected, smoke production may drop to lower values. Tests show that covering EPS-insulation with non-combustible materials/boards would have a significant influence on the smoke production in case of fire (Lie, 1981).

As mentioned, EPS slowly begins to soften at temperatures above 100 °C and then starts to shrink. When heated further it melts. Upon prolonged exposure to the action of heat, the melt gives off gaseous, flammable decomposition products. The point at which the concentration of these products suffices for ignition by flames, sparks, etc. depends on the temperature and the duration of exposure to heat.

Production of toxic gases

Compounds such as carbon monoxide, hydrogen chloride, hydrogen cyanide, sulphur dioxide and oxides of nitrogen are recognized as harmful products; others such as water vapour and the hydrocarbons contribute little or no toxic hazard. Of those who die of smoke poisoning, most people die because they inhale large quantities of carbon monoxide (CO) (SINTEF, 2001).

Tests show that for most plastics, toxicity will initially correlate to the production of CO, HCN, and hydrogen chloride (HCl) (SINTEF, 2001).

Combustion of EPS produces a lot of dark smoke. EPS may cause hazardous smoke in a fire such as carbon monoxide, carbon dioxide, styrene, aliphatic hydrocarbons and hydrogen bromide, and is considered as toxic.

When heated, PUR and PIR give off combustible gas. Burning of PUR/PIR produces less smoke than EPS, but the smoke is still toxic and it develops HCN gas and NOx.

A protective cover over the insulation may also substantially delay the development of toxic products (Lie, 1981).

6.3 Use of fire resistant construction and non-flame retarded EPS

The best way to avoid fire spread is by appropriately protect the insulation material from any ignition source. No insulation material should be used uncovered, not only for fire performance but also for mechanical and long-term insulation properties. It is recommended by the industry that EPS should always be protected by a facing material, or be completely encapsulated (EUMEPS, 2002). Facing materials may be bricks, concrete, plasterboards, metal sheets, etc.

In some countries, e.g. Sweden and Norway, national regulation allows the use of non flame retardant EPS and other combustible insulation materials, if the total building element meets the fire safety requirements. In those countries, an alternative to the use of flame retarded EPS would be use of non-flame retarded EPS in combination with thermal barriers, covering the EPS with non-combustible materials with high thermal heat capacity, e.g. concrete. By covering the EPS/XPS with e.g. 50 mm concrete on all sides, the building element as a whole could classify to non-combustible, and could be used in constructions as external façades, floor slabs or flat roofs. Alternatively, EPS can be covered with a layer of non-combustible insulation material, e.g. mineral wool. This would especially be used on flat roofs, where the EPS is covered by e.g. 30 mm stone wool.

In all solutions, the layer of non-combustible material will have to fully cover the EPS on all sides and precautions have to be taken to avoid openings and penetrations in the construction (e.g. around windows).

The following sections refers to the applications of EPS shown in Section 3.3

External façades and basements walls

Fire might spread in different ways through the combustible insulation in the exterior wall. A fire could spread from burning flammable insulation through openings in the façade and into the building, or from a fire inside the building through openings. When combustible insulation is used in the exterior, it is important that the bearing and covering material is non-flammable. There should not be cavities in the façade that will provide supply of oxygen and could easily spread fire.

External walls can be designed in different ways. One solution is to place insulation in between two concrete slabs. In this type of construction, the insulation material must have enough compressive strength in order to take up the pressure load between the two slabs. Plastic foams and mineral wool are commonly used. Inside the construction, the insulation material is well protected from fire. Attention has to be given to the risks for fire spread vertically between the elements in multi-storey buildings. Fire brakes in form of using incombustible insulation materials at the connections and between the different stories are needed. Flame retarded EPS/XPS in such a construction is not sufficient to stop fire spread (Elmroth, 2011).

In a traditional wood frame wall, the insulation material is normally mineral wool, whereas the external insulation may be EPS/XPS or mineral wool.

Basement walls are often insulated on the outside. EPS without flame retardant can be used for such an application, but special qualities of stone wool are also possible. EPS is the cheapest product for this application. The insulation material in this application is protected from fire and no flame retardant is needed (Elmroth, 2011).

By covering (at all sides) the combustible insulation, e.g. with cement plaster, or by use of plasterboards, the insulation would be covered, and the risk of fire spreading is reduced.

Flat roof insulation

Applying combustible insulation on flat roofs is an often used solution worldwide. A fire could spread to the roof from the façade, through the roof construction or through penetrations or leaks in the roof. To prevent the risk of fire spreading, combustible insulation should be covered with non-combustible material. Reported assessments (SINTEF, 2003) have investigated the use of combustible insulation on flat roofs. The study concludes that in order to prevent the spread of fire in buildings, it is very important to have a thermal barrier between the insulation materials of thermoplastic and the metal roofing. The thermal barrier could be a plasterboard or a layer of concrete. The thermal barrier most be solid and stick to shape even if heated.

Covering with a layer consisting of non-combustible insulation such as mineral wool at the top of the combustible insulation would reduce the risk of fire spread. An alternative solution would be to divide the areas with combustible insulation into separated areas by use of fire barriers to limit a possible fire, but covering would still be recommended.

Use of non-flame retarded EPS is allowed in Norway on flat roofs, but it requires sectioning or covering according to national building codes. The use of non-combustible insulation, for example mineral wool, would make a better fire safety design.

Sandwich panels

Sandwich panels with core material of polymer insulation are widely used construction elements, especially when it comes to rooms for refrigeration and freezing, or in exterior walls. Sandwich panels are also often used as interior partitions and interior panels in the food industry.

Most often, sandwich panels are covered with plates of steel or aluminium, but sandwich panels could also be coated with several types of sheet materials, such as laminates, plasterboards or wood-based panels. Plaster or wood-based panels are sometimes used to improve the elements’ fire properties or mechanical strength.

Sandwich panels are vulnerable in terms of performance by the penetration of the elements and leaks in the element joints. Leaks and penetrations may represent a significant risk of fire spreading.

Sandwich elements with non-combustible covering with a core of PIR are often classified as B-s2,d0, while elements with polyurethane can achieve B-s3,d0 (Byggforsk, 2007).

EPS sandwich panels would likely provide Euroclass B-s3, but this would likely depend on whether the insulation is flame-retardant or not.

Slab on ground below floating floor

Slab on ground is a very common foundation method in buildings. Insulation placed underneath the concrete slab is considered to be the most fire safe solution. In the finished foundation, the insulation materials are well protected from fire exposure. EPS without flame retardant or slabs of heavy stone wool are excellent materials for insulation underneath the slab. There is no advantage of using fire resistant materials or materials with flame retardant in this construction. Light expanded clay is also a common used solution underneath the slab although the layer has to be thicker due to the higher thermal conductivity of the expanded clay.

If the load is not too big, EPS would be the most cost effective insulation to use. XPS is more expensive and is used when the loads from the building are higher. Heavy stone wool is a god alternative insulation, but it is more expensive than the EPS.

A slab on ground construction can also be insulated above the concrete slab below a floating floor. In this type of construction, the insulation is covered by floating material. Floating floor with non-combustible covering is preferably. There is less advantage of having insulation with flame retardant (Elmroth, 2011). EPS without flame retardant is a suitable insulation material. Stone wool is a good alternative.

Use of combustible insulation underneath floating floors provides covering, preferably with non-combustible boards.

6.4 Assessment of alternatives in view of building fire safety

Use of non-combustible insulation would in all cases provide a better fire safety design in preventing spread of fire. Use of combustible insulation in combination with thermal barriers, makes the need for flame retarded EPS decrease. In many cases it would then be possible to use the EPS which is not flame-retardant, without reducing fire safety performance in the construction. Application for use of such structures would e.g. be in the facade, the floor or on flat roofs.

Combustible insulation could in most cases be replaced with non-combustible insulation. The use of mineral wool would in these cases be a good choice as regards fire safety. Alternatively, the use of wood fibre or other more or less combustible materials would be possible, but they would in most cases like EPS require covering with non-combustible materials, e.g. gypsum boards to meet national regulations and building codes.

As regards the various plastic foam insulation materials they are all flammable and produce large amounts of smoke when burning. EPS forms burning droplets, while PUR and PIR does not. They all contribute to fire load. Flame retardant additives do not eliminate these conditions, only reduce them. Flame retardant EPS will have a lower flammability and a slower flame spread than non-flame retardant EPS. Production of smoke and toxic gases will be reduced, but will still be present. When heated, PIR would not melt, but chars and makes an insulating layer which protects the underlying material.

Replacement of EPS with other combustible insulation products such as PIR or PUR would in many cases be a good option.

The dominating insulating materials that can be an alternative to flame retarded EPS/XPS are non-flame retarded EPS/XPS, mineral wool, PIR or PUR. In some special applications, cellulose fibre and cellular glass would be an option, but currently the market is small for these materials.

It is clear that as long as the combustible insulation is fully covered by non-combustible material forming a thermal barrier, flame retardant is less needed. It is then important that the insulation stays covered even when heated and exposed to fire. The properties as regards reaction to fire of the assessed insulation materials are summarised in Table 6.2.

Table 6.2 Summary of properties (reaction to fire) regarding building fire safety

Material/technique	Combustible (Euroclass)	Development of toxic smoke	Burning droplets	Contribution to fire load
EPS sheets (flame retarded)	E	Yes	Yes	Yes
EPS sheets (non-flame retarded)	F	Yes	Yes	Yes
Polyisocyanurate (PIR) sheets (flame retarded)	D	Yes	No	Yes
Stone wool	A1, A2	Non/less	No	No (negligible)
Glass wool	A2	Non/less	No	No (negligible)
Wood fibre insulation board (flame retarded)	E	Yes	No	Yes
Foamglass	A1	Non	No	No

7. Resource consumption and environmental effects in a life cycle perspective

In order to compare the resource consumption and environmental effects of the use of the different insulation materials the following section presents a comparative screening life cycle assessment of the materials.

For many of the applications, use of alternatives to flame retarded EPS may introduce some minor chances to the other materials of the building element such as fixation systems, supporting structures, adhesives, surface treatment, etc. For an in-depth comparison of the materials, a full life cycle assessment (LCA) of the entire building element would be needed, but the results of the assessment would only apply to the specific building element and the specific materials used. It has been beyond the scope of the current study to prepare full LCAs.

For this reason it has been chosen to compare the insulation materials only, recognising that for some applications necessary changes in other materials may have some impact on the overall assessment.

For many of the materials, LCA's have been undertaken for the lifecycle stages from cradle to gate (including raw material extraction, transport of raw materials and the manufacturing of the material). The assessments have been undertaken using different methodologies, reference years, geography, etc. and the exact insulation material is often not reported. Consequently it is difficult to assess whether the materials compared can actually be used for the same applications. As shown in previous sections e.g. the density of the materials varies considerably, depending on the application and this have a significant impact on the results of the assessment.

For the present screening assessment it has been chosen to use data from German Environmental Product Declarations (EPD's) developed according to the ISO 14025 standard. Environmental Product Declarations for various insulation materials have been developed for manufacturers or trade organisations by the Institut Bauen und Umwelt e.V. (Germany). The EPDs are available at the website of the Institute (IBU, 2011). The Environmental Product Declarations included LCA's carried out in accordance with the ISO 14040 standard for Life Cycle Assessments and the acknowledged LCA tool GABI has been used for the calculations and assessment.

7.1 Functional unit and system boundaries

In order to compare the materials, it is necessary to define the functional unit for the assessment and the systems boundaries.

Functional unit

The functional unit is in ISO 14040 defined as the quantified performance of a product system for use as reference unit in a LCA study. The key performance aspect of the insulation products is the insulation capacity of the applied material. The thermal resistance (the R-value) measured in $m^2 \cdot K/W$ has been generally accepted as an adequate functional units for LCAs of thermal insulation products (Schmidt *et al.*, 2004).

In this assessment, the materials will be compared on the basis of 1 m^2 of an insulating material suitable for external façade insulation with a thermal resistance of 2.875 $m^2 \cdot K/W$. This corresponds to the thermal resistance of a 10 cm thick EPS board with a thermal conductivity of 0.035W/(m ·K).

System boundaries

The system boundaries defines which life cycle phases to be included in the LCA and the boundaries between the technological system and nature, between the life cycle concerned and life cycle of other technical systems, time horizon, and the geographic area.

For a full cradle to grave LCA the analysis would include extraction of raw materials, transport of raw materials and manufacturing of the material (these three stages are here designated “cradle-to-gate”), transport to the user, the use phase and the disposal of the material. The German EPDs varies in which life cycle stages are covered by the LCA and several of the LCAs only cover the cradle to gate.

The LCA of the environmental declaration for EPS (Styropor®) for walls and roofs (IBU, 2011) includes the transport of the materials to the user. The energy consumption by transport of the products is only 0.2% of the primary energy consumption for the cradle-to-gate. Even though the energy consumption for transport may be higher for stone wool, cellular glass and wood fibre boards due to higher weight, the consumption is still considered to be small compared to the manufacturing. In a Japanese comparison between XPS, PUR and glass wool transport, both national and international, the CO2 emission from transport for all materials was less than 5% of emission from manufacture (Inoue *et al.*, 2010).

For the comparison, the transport to the user will consequently be excluded. The environmental impacts of the transport of the insulation materials is considered to be small compared to the total cradle to grave impacts.

The main impact of the insulation materials is the positive impact of the energy saving in the use phase, but this will be the same for all materials as the comparison is between solutions with the same thermal resistance. It should be noted that the use of insulation materials in buildings typically saves more than 100 times the environmental impacts associated with the production and disposal of the materials (Schmidt *et al.*, 2004).

Other impacts from the use phase of insulation materials may be due to releases of toxic chemicals or dust and releases of blowing agents from foams.

The effects of releases of toxic chemicals (e.g. HBCD) and dust/fibres are in general difficult to compare between materials releasing different chemicals or dust/fibres (Schmidt *et al.*, 2004). The reason is that internationally agreed normalisation or equivalence factors for the effects of the toxic substances on the environment and human health do not exist or are very uncertain as total emission and equivalence factors only exist for a limited number of substances. The effect categories for environmental and human toxicity are consequently excluded from the EPDs used for this study, and are in general often excluded from comparative LCAs. These possible effects of toxic chemicals and fibres in a life cycle perspective are therefore described and assessed qualitatively in Chapter 8. They are included in the overall assessment in the summary and conclusions of this study (Chapter 9).

Historically, some foams have been produced with blowing agent with a significant global warming and ozone layer depletion potential. In order to compare the lifetime global warming potential (GWP) of insulation materials, Wilson (2010) has calculated the lifetime GWP for a range of insulation materials on the basis of the use of energy resources and lifetime emission of blowing agents with global warming potential. The contribution from the use phase for EPS (pentane blown) and PIR (pentane blown) to the lifetime GWP was small, whereas XPS and spray PUR foams (applied on-site) using HFC-245fa and HFC-134a, respectively, as blowing agents had a lifetime GWP about 50 times higher than for the EPS and PIR. The foams assessed in the current study (the EPS and PUR/PIR boards) are produced with CO_2 or pentane as blowing agents, and the contribution from the use phase to GWP is very small. The pentane is mainly released during conversion of the raw material to insulating board and this is included in the cradle-to-gate phases, and the released pentane results in a relatively high summer smog potential of the manufacturing of EPS.

The use phase will consequently be excluded from the assessment and it will furthermore be assumed that the insulation materials last for the same number of years before they are disposed of. For the considered materials the actual life-time of the materials are typically governed by the life-time of the building element and not the life-time of the insulation, according to current knowledge.

The remaining phases are the cradle-to-gate and the disposal. Whereas the cradle-to-gate is relatively well defined, the disposal will be very sensitive to the actual disposal treatment applied. It makes a significant difference whether the materials are recycled, incinerated or landfilled. If the EPS for instance is disposed of for incineration more than 1/3 of the energy used for the manufacturing (the energy content of the material) is regenerated. The assumptions regarding disposal for each of the materials will be described in the next section.

It should be noted that the environmental effects of electricity consumption (and to some extent other energy consumption), is very dependent on the actual conditions for production of the electricity (renewable energy, coal, nuclear power, etc.) and different methods for allocating environmental effects from the production of electricity exists. These methodologies might differ among the different EPDs. For this reason, primary energy consumption (renewable and non-renewable) is the most robust property for the comparison of the materials. Some uncertainty may be introduced in the comparison of different environmental effects due to this situation.

7.2 The comparative analysis

When comparing between different insulation materials, it is essential to compare grades which can in fact be used for the same applications. As described earlier, EPS is available in a range of grades and densities. According to the LCA of the EPD for EPS insulation, the primary energy consumption (and the resulting environmental effects) for the manufacturing of 1 m^3 flame retarded EPS range from about 700 MJ for EPS of a density of 15 kg/m^3 (corresponding to EPS 70) to about 1,400 MJ for EPS of a density of 30 kg/m^3 (corresponding to EPS 200).

In order to use comparative materials for the assessment, it has been chosen to use material property data (thermal conductivity and density) of specific products marketed for use for external façade insulation. These data are compared with LCA data for similar grades (approximately) from the EPDs which in many cases provide data for different grades of the materials. For e.g. EPS and the PUR/PIR the EPDs are prepared by the trade organisations and the LCA data represent typical values for the industry in Germany. Please note that the calculated energy consumption and environmental effects consequently may not be applicable for the specific products, as the specific conditions for the manufacturing may differ from the condition used in the LCA of the EPD.

Comparison of cradle-to-gate

The results of the screening assessment for the life cycle phase from cradle to gate, as well as the parameters of the materials, are shown in Table 7.1. The basic data obtained from the EPDs are shown in Annex 1. Due to differences in the thermal conductivity of the materials, the thickness of the material to meet the functional unit varies. The major difference is, however, the large differences in the weight of the materials ranging from 2.3 kg to 23.3 kg.

Primary energy consumption (cradle-to-gate)

Total primary energy consumption for the cradle-to-gate varies from 139 MJ for the stone wool to 746 MJ for wood fibre board. The primary energy consumption represent the total energy content of energy raw materials whether the raw materials are used for production of energy or used for the manufacturing of hydrocarbons such as plastic materials. The energy content of the plastic or wood materials is consequently included in the total primary energy consumption.

The primary energy consumption is 186 MJ and 192 MJ respectively for two grades of EPS both indicated as used for external wall insulation, but of different quality. The stone wool and PUR/PIR both have lower primary energy consumption. It should be noted that the primary energy consumption for the production of the stone wool used here (Deutsche Rockwool Mineralwoll GmbH & Co. OHG) is relatively small compared to other stone wool products. The product has a total energy consumption for production (cradle-to-gate) of 12.9 MJ/kg whereas the EPD for another stone wool product (Saint-Gobain ISOVER G+H AG) indicates a total primary energy consumption of 26.3 MJ/kg. The comparison with the EPS insulation would come out significantly different if the comparison was done with this product.

The highest total energy consumption is for the wood fibre board, and even though the major part is from renewable energy resources the consumption of non-renewable primary energy is higher than for the foams and stone wool. High primary consumption for production of insulation of natural fibres was also found in a LCA by Schmidt et al. 2004, who found the total primary energy consumption for manufacturing of insulation materials of flax and paper wool to be significant higher than the energy consumption for manufacturing of stone wool (Schmidt *et al.*, 2004).

It should be noted that for all materials the distribution between energy resources could be different for other manufacturers of the materials.

Environmental effects (cradle-to-gate)

The global warming potential (in CO_2 equivalents) is higher for the stone wool and the cellular glass than for the plastic foams, reflecting that a significant part of the energy resources used for the foams are not combusted, but used to produce the materials and the energy (and the carbon) is thus embodied in the foams. The CO_2 will later be released when the foams are incinerated or burned by disposal and for the global warming potential of the total life-cycle, it is essential whether the materials are incinerated with energy recovery (whereby it substitutes for other energy resources). The negative global warming potential of the wood fibre board of -27.3 kg CO_2 equiv is due to the fact that CO_2 which has been absorbed by the growth of the wood is trapped in the wood of the fibreboard. The CO_2 will be released again if the fibreboard is incinerated or burned by disposal. The life-cycle CO2 balance will be very dependent on the disposal scenario as discussed below.

The global warming potential are very much associated with the use of energy raw materials and the actual energy resources used have significant influence on the level of the effects. It makes a significant difference whether the used electricity comes from a nuclear power plant, water power plant, wind power plant, gas power plant or a coal power plant. For three of the assessed effect categories, ozone layer depletion potential, acidification potential and eutrophication potential, the EPS materials have smaller effects than alternatives. For summer smog potential (identical to photochemical oxidants formation) the EPS materials have a significantly larger potential, reflecting higher releases of VOC (volatile organic compounds).

Resource depletion (cradle-to-gate)

The resource consumption is not quantified in the EPDs. For these materials, however, the total non-renewable energy consumption can be used as an indicator of the resource consumption for the production of the materials. As demonstrated in other LCAs of insulation materials, the non-renewable energy consumption is more or less correlated with the abiotic resource depletion in kg crude oil-equivalents (see e.g. Table 7.3, discussed later).

For the plastic foams the consumption of fossil fuel resources are considered to represent the most significant resource consumption, as the material itself is based on the fossil fuels. For the stone wool and cellular glass the consumption of mineral resources such as rock or sand, may have some impacts of the total resource consumption. Rock and sand is in general not considered scarce resources and normalisation and weighting factors necessary for the assessment of the severity of the resource depletion have in general not been developed for these resources. For these materials, the use of non-renewable energy resources is also considered the most severe resource consumption.

Table 7.1 Properties and results of the comparison of insulation materials for1 m^2 and a thermal resistance of 2.857 m^2·K/W. Results represents manufacture (cradle-to-gate) of the materials only.

	Flame retarded EPS W/D 35*	Flame retarded EPS W/D 40*	Stone wool **	PUR/PIR ***	Wood fibre board ****	Cellular glass *****
Thermal conductivity, W/(m·K)	0.035	0.040	0.036	0.027	0.043	0.038
Thickness,cm	10	11.4	10.3	7.7	12.3	10.9
Nominal density, kg/m³	23	16.6	105	30	180	100
Weight per m^2, kg	2.3	1.9	10.8	2.3	21.1	10.9
Results						
Non-renewable primary energy, MJ	185	192	139	174	201	166
Renewable primary energy, MJ	1.0	0	1.1	3.7	544	100
Total primary energy, MJ	186	192	140	178	746	267
Global warming potential (GWP 100), kg CO_2 equiv.	6.2	6.5	12.5	10.3	-27.3	11.9
Ozone layer depletion potential, kg R11 equiv.	1.7E-07	1.9E-07	9.2E-07	1.7E-07	8.9E-07	8.1E-08
Acidification potential, kg SO_2 equiv.	0.013	0.014	0.081	0.033	0.029	0.023
Eutrophication potential, kg PO_4 equiv.	0.001	0.001	0.009	0.003	0.011	0.003
Summer smog potential, kg C_2H_4 equiv	0.035	0.042	0.006	0.005	0.002	0.002

The following products have been used for the comparison of the technical properties:

*	EPS-Hartschaum (Styropor) W/D-035 and W/D-040
**	Rockwool Coverrock
***	Purenotherm
****	NBT/ Pavatex DIFFUTHERM external wall insulation
*****	Foamglas w+f

Normalisation of the results

In order to analyse the relevance of the impacts of the functional unit to the total impact of the society, a normalisation is necessary. The normalised figures indicate, for each effect category (global warming potential, eutrophication, etc.), the share of the impact caused by the functional unit investigated, of the total impact in this category in the region of interest . Normalised impact values can be compared across impact categories. For example the relative contribution from a product to global warming can be compared to that of ozone layer depletion, thus giving an indication of the relative importance of the different effect categories.

The normalisation is the conversion of the estimated impact by dividing it by a relevant reference value. The reference value used here is the average impact for each effect category of a citizen in Western Europe. The normalisation figures are estimated and regularly updated by the Dutch research institution CML, and the values used here are derived from the latest version of the reference values as given in the GABI LCA tool, which has also been used for the German EPDs.

The normalised values in the unit milli-person equivalent are shown in Table 7.2. A milli-person equivalent is 1/1000 part of the average impact per capita for the effect category concerned. The data shows that the functional unit contribute less to the two categories ozone layer depletion and eutrophication, and the differences between the materials for these two parameters are consequently of lesser importance.

It should be noted that it is not possible on the basis of these data to conclude in absolute terms to what extent the contribution of insulation materials to the different effect categories can be considered to be important..LCAs are basically a methodology for comparing different solutions meeting the functional unit.

Table 7.2 Same data as in Table 7.1, but normalised to Western European average per capita consumption

	Flame retarded EPS W/D 35*	Flame retarded EPS W/D 40*	Stone wool **	PUR/PIR ***	Wood fibre board ****	Cellular glass *****
Global warming potential (GWP 100), milli-person equiv.	0.506	0.529	1.019	0.835	-2.221	0.966
Ozone layer depletion potential, milli-person equiv.	0.001	0.001	0.004	0.001	0.004	0.000
Acidification potential, milli-person equiv.	0.183	0.194	1.133	0.456	0.405	0.317
Eutrophication potential, milli-person equiv.	0.040	0.043	0.276	0.104	0.335	0.077
Summer smog potential, milli-person equiv.	1.635	1.933	0.261	0.253	0.091	0.096

Comparison of entire life cycle

As mentioned above the manufacturing and disposal phases are considered to represent the largest difference among the materials.

For the disposal phase it has a large impact whether the materials are recycled, down-cycled (replacing another material of lower value), incinerated or landfilled. The most optimal disposal method, recycling and down-cycling of the materials, would not be the main disposal method in most countries (if any). In countries with widespread use of municipal solid waste incineration (e.g. Germany or Denmark) the EPS, PUR/PIR and wood fibre boards would typically be incinerated with energy recovery while stone wool and cellular glass would be disposed of to landfill.

Under Danish conditions in 2007 67% of the energy content of the waste was converted to district heating while 15% was converted to electricity. It will here for the calculations be assumed that under optimal conditions 80% of the energy content of the combustible materials is converted to useful energy and will thereby substitute for other energy sources. The high energy efficiency can only be obtained when the generated heat by the incineration is used for district heating, which would not be the situation in many parts of the world. As the use of renewable energy resources at present is limited, it will here be assumed that the energy recovered by the incineration substitute for the use of non-renewable resources. The EPD of EPS assume that 99% of the energy produced by the incineration substitute for non-renewable resources, but it will here for simplicity for all materials be assumed that it is 100%.

The calculation done in this way is somewhat simplistic, as the energy efficiency of the energy systems, which the incineration substitutes, for should also be taken into account. On the other hand, the assumption that 80% of the energy content is recovered only applies to quite efficient incinerators.

The results show that, if incinerated with energy recovery under optimal conditions, the plastic foams have a lower lifecycle consumption of non-renewable primary energy than the stone wool and the cellular glass. If not incinerated with energy recovery the situation is opposite. In many countries in Northern Europe and North America incineration with energy recovery will be the main disposal method, but this is not the situation in most other parts of the world. If the wood fibre boards are incinerated under optimal conditions the boards can be considered carbon neutral as the non-renewable primary energy consumption for the production of the boards is outweighed by the non-renewable primary energy resources saving by incineration of the boards. If not incinerated, the non-renewable primary energy consumption is in fact higher for the boards than for the other insulation materials.

Table 7.3 Properties and results of the comparison insulation materials meeting the functional unit of 1 m^2 and a thermal resistance of 2.857 m^2·K/W. Results represent manufacture (cradle-to-gate) plus disposal.

	Flame retarded EPS W/D 35*	Flame retarded EPS W/D 40*	Stone wool **	PUR/PIR ***	Wood fibre board ****	Cellular glass *****
Manufacturing (cradle-to-gate)						
Non-renewable primary energy, MJ	185	192	139	174	201	166
Renewable primary energy, MJ	1.0	0	1.1	3.7	544	100
Total primary energy, MJ	186	192	140	178	746	267
Disposal						
Calorific value, MJ/kg	40	40	-	30	12	-
Energy recovery with incineration, MJ	-74	-61	0	-55	-203	0
Manufacturing + disposal						
Total energy consumption	111	131	139	119	-1	166
Total non-renewable primary energy, MJ	1	0	1	4	544	100
Total renewable primary energy, MJ	112	131	140	123	543	267

7.3 Results of other life-cycle screenings

Comparative LCA of Biofoam®, EPS, PUR foam and stone wool

Nordegraaf *et al.* (2011) has recently prepared a comparative LCA of a newly developed insulation material, Biofoam® and EPS, PUR foam and stone wool (Rockwool). Biofoam® is a polymeric foam prepared from lactide produced from sugar cane. The material has not been assessed in the present study. In the LCA, the authors compare the impacts of the production of 1 m^2 insulation material with a thermal resistance of 5 m^2·K/W corresponding to 1.8 times the resistance of the functional unit used in the assessment in the present study. The results are shown in Table 7.3 below. According to the study, the energy consumption (non-renewable and renewable) for the manufacturing of the EPS is lower than the energy consumption for the manufacturing of PUR foam and stone wool. It may reflect that the comparison has been done with materials produced under different conditions than the materials assessed in the current study, and illustrates the uncertainty when comparing across materials. If energy recovery by disposal is considered for the EPS and the PUR foam, whereas the stone wool is assumed to be landfilled, the comparison is even more in the favour of the EPS. EPS has higher potential as concerns photochemical oxidants formation and lower potential for the other effect categories which is in accordance with the results presented above.

Compared with the results of the current study, the main difference is the significantly higher non-renewable energy consumption for manufacturing of the PUR foam and the stone wool, which also explain the higher potential for the environmental effects apart from photochemical oxidation.

Table 7.4 Properties and results for the production (cradle-to-gate) of 1 m^2 insulation material with a thermal resistance of 5 m^2·K/W

	BioFoam	EPS	PUR Foam	Stone wool
Thermal conductivity, m^2·K/W	0.036	0.036	0.026	0.042
Nominal density, kg/m^3	20	20	40	120
Thickness, cm	18	18	13	21
Mass, kg/functional unit	3.6	3.6	5.2	25.2
Results				
Non-renewable energy use (gross caloric value, MJ	222	418	529	687
Renewable energy use (gross caloric value), MJ	202	3	8	69
Abiotic resource depletion, kg crude oil equiv.	4.6	8.7	10.6	13.9
Global warming potential (GWP100 yrs), kg CO_2 equiv.	8.1	16.6	21.8	41.3
Acidification potential, kg SO_2 equiv.	0.10	0.04	0.09	0.22
Photochem. oxidant. formation (smog), kg C_2H_4 equiv	0.010	0.039	0.010	0.020
Eutrophication potential, kg PO_4 equiv	0.045	0.005	0.016	0.029
Farm land use, m^2/year	7.6	0.013	-	9.8

Lifetime Global Warming Potential

As mentioned above, in order to compare the lifetime global warming potential (GWP) of insulation materials, Wilson (2010) has calculated the lifetime GWP for a range of insulation materials on the basis of the use of energy resources and lifetime emission of blowing agents with global warming potential. The EPS (pentane blown), rigid mineral wool and PIR (pentane blown) comes out with nearly the same lifetime GWP, whereas XPS and spray PUR foams using HFC-245fa and HFC-134a, respectively, as blowing agent have a lifetime GWP about 50 times higher. Densely packed cellulose (paper wool) has the lowest GWP.

8. Human health and ecotoxicology

Potential human health effects and ecotoxicological effects of the direct use of the insulation materials would mainly concern the potential effects of chemicals used for the production or present in the materials and the releases of fibres, particles and dustin the working environment during construction work and in the indoor climate.

8.1 Potential effects of chemicals in the materials

EPS

The potential effects of HBCD used in flame retarded EPS are well described and they are the background for initiation of this study. In December 2009 HBCD was considered by the Executive Body of the UNECE Convention on Long-range Transboundary Air Pollution (LRTAP) to meet the criteria for persistent organic pollutants. The POP review committee under the Stockholm Convention furthermore concluded that HBCD should be considered a global POP in October 2010 (UNEP, 2010). The use of HBCD is subject to, or under inclusion in, severe regulation in a number of countries. By way of example, HBCD is on the list of Candidate List of Substances of Very High Concern (SVHC) for authorisation under the REACH regulation within the EU.

The adverse effects concluded by the experts in the committee are high toxicity to aquatic species and reproductive, developmental and neurotoxic effects in mammals and birds.

During the lifecycle of the insulation materials, HBCD may be released at different stages: by the production of the substance and the manufacture of the flame retarded EPS, installation and demolition of insulation materials, during the use phase and by the ultimate disposal of the insulation materials. Releases of HBCD from the different life cycle stages have among other been evaluated by the EU Risk Assessment (EC 2008), IOM (2009) and Morf *et al*. (2008).

Morf et al. (2008) have, based on a substance flow analysis for HBCD in Switzerland, estimated that the emission of HCBD is increasing and that construction materials are responsible for the majority of the emissions. Diffuse atmospheric emissions of HBCD from installed EPS and XPS insulation panels is estimated to account for about half of the atmospheric emissions in Switzerland. As the stock in the use phase is growing, these diffuse emissions are projected to increase in the coming years.

The release estimates of the EU Risk assessment indicate another release pattern (EC, 2008). The releases from the different life stages for EPS/XPS account for about 97% of the total estimated releases of HBCD to air in the EU of 508 kg. The major sources are estimated to be industrial and professional use of EPS and XPS whereas the service life stage is estimated to account for approximately 10% of total estimated releases. The report emphasises that there is a big uncertainty in future releases of HBCD from demolition of buildings insulated with flame retarded polystyrene (EPS and XPS).The releases from future demolition is estimated to be more than ten-fold higher than predicted current releases from construction. The estimate of total releases does not include current releases from landfills. According to the risk assessment, emissions from landfills may prevail for a very long time, often thousands of years or longer. Polymer end-products containing HBCD will accumulate on landfill sites. Degradation of the matrix will sooner or later cause release of the substance from the matrix. Besides this, biodegradation of HBCD that occur in the landfill will limit potential future emissions. Considering the large amount of HBCD which will accumulate in landfills, landfills may likely be the main long-term sources of HBCD releases.

PIR/PUR

PUR/PIR foams are manufactured in grades with or without flame retardants. The flame retardants are either used reactively (incorporated in the polymer structure) or used additively. For both the additive and the reactive flame retardants halogenated and non-halogenated flame substances are marketed. Examples of the flame retardants marketed for rigid PUR/PIR foams for the building sector are shown in the table below. It should be noted that for the reactive flame retardants, the specific substance is only present in trace amount in the final polymer.

Table 8.1 Examples of flame retardants marketed for used in rigid PUR/PIR foams

Name	CAS no	Reference	EU Classification	Remark
Reactive flame retardants				
2-(2-hydroxyethoxy)ethyl 2-hydroxypropyl 3,4,5,6-tetrabromophthalate	20566-35-2	Albemarle, 2011	none	
Tetrabromophthalic anhydride based diol (Firemaster 520)	proprietary	Chemtura, 2011b	none	
N,N-dihydroxyethyl-aminomethane-phosphonic acid- diethylester	2781-11-5	Lanxess, 2011	none	
Halogenated polyetherpolyol	68441−62−3	Solway, 2007	none	
Additive flame retardants				
Tris-(2- chloroisopropyl)-phosphate (TCPP or TMCP)	13674-84-5	Lanxess, 2011	none	EC Risk Assessment present (EC, 2008)
Dimethyl propane phosphonate (DMPP)	18755-43-6	Lanxess, 2011	n one	
Triethyl phosphate (TEP)	78-40-0	Lanxess, 2011	Xn; R22, harmful if swallowed.	
Ammonium polyphosphates (Exolit AP 422, 462)	68333-79-9	Clariant, 2011	none	

The flame retardants may be used in combinations. As an example from one manufacturer, the polyol part for manufacturing insulation materials for the building sector contain15-20% halogenated polyetherpolyol (CAS No 68441−62−3) and 5-10% TCPP.(Solvay, 2007). Please note that the concentration will be significantly lower in the final PIR).

TCPP has been reported by the industry as the “first choice” for rigid PUR foam used in the construction industry (EFRA, 2002). It should not be confused with TCEP (tris(2-chloroethyl)phosphate, formerly used as flame retardant in PUR, and classified carcinogenic and toxic to reproduction in the EU.

A European Community Risk Assessment and an OECD SIDS (OECD,1998) have been prepared for TCPP. The substance is not classified in the EU. The SIDS concludes that TCPP is harmful to aquatic organisms while the EC Risk Assessment concludes that data presented in the report are consistent with no classification for the environment being necessary. TCPP does not meet all of the PBT criteria. The EC Risk Assessment report states regarding human health, that the data presented are consistent with the classification R22 (harmful if swallowed) but points at the lack of data e.g. on carcinogenity. The Risk Assessment concludes that consumers are potentially exposed to negligible amounts of TCPP in rooms containing closed-cell rigid foam.

Of the other flame retardants triethyl phosphate (TEP) is classified Xn; R22, harmful if swallowed.

Although still some controversy about the potential effects of the halogenated phosphorous flame retardants in general, it can be concluded that the substances typically used in the PUR/PIR has not been demonstrated to meet the PCB criteria and are not classified CMR substances (carcinogenic, mutagenic or reprotoxic).

The flame retardants in these foams may be released to the environment from all life cycle stages. No attempt has been done in this study to estimate the actual releases of the substances.

Stone wool

The fibres of mineral wool (stone wool and glass wool) have traditionally been bonded with a resin binder, based on phenols and formaldehyde. The concentration of the binder is indicated to be in the range of 1-17% depending on the specific application. Most of the formaldehyde is removed by the manufacturing process. Stone wool may potentially release formaldehyde from the construction into indoor air. Neuhaus *et al.* (2008) demonstrated formaldehyde emission rates from uncovered stone wool falling from 72 to 50 $\mu g/m^2h$ over a period of 28 days. Lower rates were found if the insulation was covered with steel plate. The study concluded that the emissions from mineral wool in building constructions are mostly far below international indoor limit values for formaldehyde.

When stone wool is heated to approximately 200°C for the first time(s), release of binder components and binder decomposition products occurs. General dilution ventilation and/or local exhaust ventilation should be provided as necessary to control exposure to fumes when high temperature appliances are first put into service, but this only concern the use of the stone wool in industrial settings as insulation in high temperature processes.

Formaldehyde is classified carcinogenic in the European Union (Carc. Cat. 3; R40). Several manufactures have in recent years introduced alternative binders. As an example the Ecose® technology for manufacturing of rock wool and glass wool applies a bio-based formaldehyde-free binder technology (the exact composition is proprietary; Knauf, 2011a).

Wood fibre boards

The wood fibre boards typically contain in the range of 2-8% binder. The binders may be based on polyurethanes or polyvinyl acetate. One type of boards is reported to contain 1% aluminium sulphate. Aluminium sulphate has been reported as used as flame retardant for cellulose, which is probably the function of the substance in the boards. The available datasheets on wood fibre boards does not indicate the presence of any chemicals of concern in the boards.

Cellular glass

The cellular insulation materials do not contain any harmful chemicals (see next section regarding dust) (Foamglas, 2011d)

8.2 Potential effects of fibres and dust

EPS, PUR/PIR and wood fibre boards

EPS, PUR/PIR and wood fibre boards do not release hazardous fibres of dust during mounting, during the use phase or by disposal of the materials. It is recommended in Material Safety Data Sheets (MSDS) to wear safety goggles and dust mask during cutting to protect the user from the small, non hazardous, dust particles.

Stone wool

Stone wool like other mineral wools consists of long mineral fibres.

Stone wool has historically been suspected to be carcinogenic. The International Agency for Research on Cancer (IARC) has in their evaluation on man-made vitrous fibre concluded that insulation glass wool, continuous glass filament, rock (stone) wool and slag wool are not classifiable as to their carcinogenicity to humans (Group 3). IARC (2002). The monograph furthermore concluded that two newly developed (in 2002), less biopersistent fibres (an alkaline earth silicate (X-607) wool and a high-alumina, low-silica (HT) wool) have been tested in well-designed, long-term inhalation studies in rats and produced no significant increase in the incidence of lung tumours and no mesotheliomas.

The high-alumina, low-silica stone wool, that has now replaced traditional stone wool, has a chemical composition that increases biosolubility and results in a fast elimination of the fibres from the lungs. High-alumina, low-silica wool dissipates approximately 10 times faster from the lungs than traditional stone wool (Rockwool, 2010). Stone wool is in the EU assigned the Risk Phrases "*Irritating to skin (R:38)"* and the Safety Phrase *"Wear suitable protective clothing and gloves (S36/37*)".

The Material Safety Data Sheet (MSDS) for stone wool notes that in the case of coarser fibres, there can be physical effects on skin, upper respiratory system (mucous membranes) and eyes that can cause temporary, self-fading effects (e.g. itching). If the workplace exposure limit is likely to be exceeded (for example when using high speed cutting tools or when working in confined spaces) disposable face masks should be used and are suitable for most applications.

Although the fibres may not result in serious health effects, the inconvenience to the construction workers may to some extent limit the use of mineral wools.

Cellular glass

Small amount of glass dust may be generated when cutting the cellular glass. When cutting cellular in a closed room, a normal extraction system with a dust filter is recommended. Respiratory protection is usually not necessary when working with the material but it is recommended when exposed to dust above recommended limits, to wear a suitable respirator with a protection factor appropriate for the level of exposure. Hand and eye protection is in general recommended. The generated is relatively heavy, so it is classified as a nuisance dust. It has not been reported to cause any pulmonary disease due to the inhalation of quartz dust (silicosis).

8.3 Summary

The results of the comparison of the substances are shown in Table 8.2 below. None of the alternative insulation materials are associated with significant health issues or releases of substances dangerous to the environment. The fibres from stone wool (and other mineral wool) have historically been suspected as carcinogenic, but the International Agency for Research on Cancer (IARC) concluded in their evaluation in 2002 that the fibres are not classifiable as to carcinogenicity to humans.

Table 8.2 Comparison of the selected insulation materials as to human health and ecotoxicology

Technical solution	Human health and ecotoxicology	
	Chemicals	Fibres and dust
Flame retarded EPS sheets	HBCCD is a PBT and POP substance.The substance may be released by the various stages of the life cycle.	No issues
Stone wool	Small releases of formaldehyde (CMR) from some types. Under normal conditions insignificant amounts in the indoor environment. Some types without binders releasing formaldehyde	Irritating fibres may result in inconvenience by construction, renovation and demolition. Fibres not classified carcinogenic.
Polyisocyanurate (PIR) sheets (flame retarded)	Halogenated phoshorous flame retardants in some types - none of the substance considered PBT or CMR or classified as dangerous to the environment	No issues
Wood fibre insulation board	No issues	No issues
Cellular glass	No issues	Small amounts of glass dust when cutting the glass. No serious effects.

9. Summary and recommendations

9.1 Comparison of alternatives to flame retarded EPS in buildings

The study demonstrates that alternative insulation materials are marketed for all applications of flame retarded EPS in buildings.

The fact that flame retarded EPS is marketed and extensively used for some building applications demonstrates that for specific applications, the material has some advantages as compared to other insulation materials, and the study has aimed at identifying the possible advantages and disadvantages of other insulation materials as compared to EPS.

The study has not aimed at providing a socioeconomic impact assessment of a restriction of HBCD in insulation materials. The study has collected information on prices of the insulation materials for different application, which partly indicate the economic impact on the users of changing to other insulation materials, but it has not quantified all possible costs of changes in design and technical solutions due to changes in the materials. Neither has the study quantified the socioeconomic impacts on the difference sectors of the insulation materials industry.

Comparison with other insulation materials

A comparison of flame retarded EPS and selected alternative insulation materials is summarised in Table 9.1.

The table shows from the left to the right:

- General technical advantages and disadvantages for the alternative insulation materials as compared to EPS for the applications assessed. For some specific applications other advantages/disadvantages may be of importance.
- Fire safety, indicated by the European Euroclass classification (see notes) and an indication of the risk of development of burning droplets and smoke.
- Qualitative description of potential impacts of chemicals and dust/fibres on human health and the environment
- Other potential environmental impacts and resource consumption:
    - Non-renewable energy consumption for functional unit (see note) for the main life cycle stages: cradle-to-gate (incl. raw material extraction, transport of raw materials and manufacturing of the insulation material) and disposal. Energy consumption is indicated for two disposal scenarios: INC, where the combustible materials are incinerated with 80% energy recovery and DEP, where all materials are deposited in landfills. The non-renewable energy consumption includes the energy content of the materials used i.e. oil used for production of the plastics is also included. The non-renewable energy consumption is considered an indicator for the main resource consumption for these materials.
    - Renewable energy consumption for the same two scenarios.
- Other environmental impacts (global warning, acidification and summer smog) for the life-stages cradle-to-gate. The table include the effect categories for which the insulation materials have significant contributions. Two other assessed environmental impacts, ozone layer depletion and eutrophication, are not shown, as the assessment indicated that the insulation materials contributed relatively less to these effects. Please note that for the materials assessed in this study

the global warming potential from the use phase is small, but this would not be the situation for XPS, and some PUR foams, with HFC blowing agents.

- Recyclability of the materials. Indicating to what extent the materials can be recycled. The notation “Recyclable with low value” means e.g. for the stone wool that the material can be recycled and thereby reducing the need for landfill capacity, but the energy consumption when using the recycled material is nearly the same as for using virgin materials and the value of the recycled material is thus very low.

The main advantage of the EPS insulation as compared with other insulation materials is a combination of low weight, high compressive strength, high insulation value, relatively good resistance to water and vapour (better for XPS), does not degenerate by moisture, it is non-irritating and has a relatively low price. Some of the key applications are external façade insulation/exterior wall insulation, sandwich panels, flat roof insulation and floor insulation, but the material is used for a wide range of applications in buildings. Except for the low price, each of the advantages are matched by some of the other materials.

All alternatives, apart from the wood fibre boards, have better performance with regard to fire safety than the flame retarded EPS. A change from flame retarded EPS to the alternatives would consequently not compromise fire safety and the alternatives would in general be able to meet the same requirements, or higher, as the flame retarded EPS.

Furthermore, all the alternatives have better properties as regards content and releases of hazardous chemicals. Flame retarded EPS contains HBCD which is a POP and PBT substance, and the substance may be released during manufacture, use and disposal. Some of the PUR/PIR foams may be flame retarded with halogenated flame retardants of some concern, but none of the substances have been demonstrated to be POPs or PBTs and none have been classified as CMR substances. The presence of HBCD in the EPS also influences the assessment of the disposal phase. Whereas recycling of the materials is of advantage when considering energy consumption and other environmental effects, recycling of EPS with HBCD may result in increased releases of this toxic substance and the presence of HBCD in the material hampers the recycling of the material.

When comparing the primary energy consumption for cradle-to gate and disposal of the insulation materials, the comparison is very dependent on which disposal scenario is selected. The study has not included energy consumption for transport to the user and the use phase which is considered to be very small (a few percentage of the cradle-to-gate consumption). Table 9.1 shows as mentioned the data for two disposal scenarios: INC where it is assumed that all combustible materials are incinerated with 80% energy recovery, and DEP where it is assumed that all materials are landfilled or incinerated without energy recovery. If the combustible insulation materials by disposal are incinerated with efficient energy recovery, as would be the situation in some countries in the Northern Europe and North America, the EPS comes out as the material with the lowest total energy consumption (renewable and non-renewable). Wood fibre boards come out better as concerns the non-renewable energy consumption, and thus the climate impact. If the combustible insulation materials are landfilled or incinerated without efficient energy recovery, which would be the situation in most countries today, the picture is different and the assessed wood fibre boards comes out as the solution with the highest energy consumption. It should be noted that the comparison is highly dependent on the energy efficiency of the production process for the specific material assessed, and the distribution between non-renewable and renewable energy resources used for the production. Other lifecycle assessments of insulation materials come out with different results if the EPS e.g. is compared with stone wool produced by a less energy efficient process.

For the cradle-to-gate, the EPS in general comes out better than the alternatives with regard to the global warming and acidification potential. The two effect categories are very dependent on the actual energy mix used for the production of the materials. For the effect category summer smog (photochemical oxidants formation) the EPS has higher potential due to the releases of pentane (a volatile organic carbon) used as a blowing agent.

The alternative materials

Stone wool (representing mineral wool materials) is marketed for the same application areas as flame retarded EPS although some minor changes in the construction may be required. For the applications concerned, the prices range from more or less the same as for flame retarded EPS to about 30% more depending on application and type. For other applications, such as cavity wall insulation and pitched roof insulation, mineral wool is in general cheaper than EPS. In scenarios where the EPS is disposed of for landfills, the stone wool (if manufactured with energy-efficient processes) has a lower life-cycle energy consumption than EPS. A disadvantage is the presence of mineral fibres which can irritate the skin, nose, mouth, throat and eyes during mounting and demolition, unless adequate personal protection equipment is used. Some types may release formaldehyde at low levels from the polymer binders. The compact stone wool types used e.g. for outer wall insulation and floor insulation have higher weight than EPS. The mineral wools are incombustible and have a better fire performance than EPS. Stone wool and other mineral wools would likely take over a significant part of the market if flame retarded EPS was not marketed.

The PUR/PIR foams (representing plastic foams) assessed in this study share some of the advantages with the EPS and can substitute for flame retarded EPS for nearly all applications. The main disadvantage as compared with the EPS is the price which typically is 10-30 % higher than the price of flame retarded EPS for the same applications, although for application where high compressive strength is required, the PUR/PIR foams are not more expensive than the EPS. The insulation efficiency for the PUR/PIR is better than for EPS which means that the insulation layer can be thinner. PUR/PIR foams (and to some extent phenolic foams) could likely take over a significant part of the market if flame retarded EPS was not marketed.

Wood fibre boards (representing natural fibre-based insulation) may be used for some of the same applications as flame retarded EPS, although the material’s vulnerability to moisture may restrict its uses for some applications. The energy consumption for the manufacturing is relatively high, but a majority is renewable energy and if incinerated with energy recovery when disposed of, the assessed boards are CO_2 neutral over the entire lifecycle. If not incinerated with energy recovery, the consumption of non-renewable energy is even higher than for EPS. The boards are significantly heavier and have a higher thermal conductivity and the use of the boards may require minor changes in the construction. Furthermore, the higher weight may require minor adjustments in the logistics at the construction site. The price of wood fibre insulation boards ranges from slightly more to significantly higher than EPS for the applications concerned.

Cellular glass has a very high resistance to compression compared to EPS and can reduce dimensions of a load bearing insulated walls in some cases. The price is significantly higher than for EPS and the glass insulation is today used for more specific applications. The cellular glass insulation is an inert and incombustible material which in addition has moisture barrier characteristics. The weight is higher than for EPS and the insulation capacity lower. Cellular glass are typically used because they have some desired technical advantages and would probably not be the first choice substitutes for general application, especially due to their price.

Fire resistive construction

In some countries, e.g. Sweden and Norway, national regulation allows the use of non flame retardant EPS and other combustible insulation materials if the total building element meets the fire safety requirements.

In those countries, an alternative to the use of flame retarded EPS would be to use of non-flame retarded EPS in combination with thermal barriers covering the EPS with non-combustible materials with high thermal heat capacity, e.g. concrete. For applications where the insulation material is in direct contract with the ground (perimeter insulation), EPS and in particular XPS have some advantages as compared with most other insulation materials. For these applications, the insulation material is typically placed between a concrete slab and the ground and the insulation material is well protected from fire exposure. In this construction there is no advantage of using fire resistant materials or flame retarded plastic foams.

For other applications, by covering the EPS/XPS with e.g. 50 mm concrete at all sides, the building element could in total classify to non-combustible, and could be used in constructions as external façades, floor slabs or flat roofs. EPS without flame retardants are used e.g. for roofs by applying a thermal barrier between the EPS and metal roofing. The thermal barrier could be a gypsum board or a layer of concrete. The thermal barrier must be solid and stick to shape even if heated. The costs of applying thermal barriers will vary considerably and have not been further investigated.

Sandwich panels, where the insulation is placed between two metal sheets (or similar) are vulnerable in terms of fire safety performance to the penetration of the elements and leaks in the element joints. Leaks and penetrations may represent a risk of fire spreading, and no actual use of non-flame retarded EPS in sandwich boards have been identified. For this application, and other applications where the application of thermal barriers would not be cost-effective, the flame-retarded EPS would need to be replaced by other flame retarded materials or non-combustible insulation materials, which are readily available in the trade.

Conclusion

Alternatives are available for all assessed applications of flame retarded EPS. The flame retarded EPS would likely be replaced by different insulation materials depending on the application, as no one alternative assessed would substitute for all EPS applications, if the use of flame retarded EPS is restricted. The alternatives typically have better fire performance and contain less problematic chemical substances. The price of the cheapest alternatives ranges from more or less the same price as for flame retarded EPS to approximately 30% more. Alternatives of significantly higher price exist, but these are typically used because they have some desired technical advantages and would, because of the price, probably not be the first choice substitutes for general application. For some applications, where flame resistance is not needed, non-flame retarded EPS would probably take over, to the extent national regulation allows.

Table 9.1 Comparison of flame retarded EPS and selected alternative insulation materials

Technical solution	Technical feasibility		Fire safety	Human health and ecotoxicological impacts		Other environmental impacts and resource consumption			Recyclability	Price of material (normalised to functional unit (FU) with similar insulation capacity)
	Advantages (as compared to EPS)	Disadvantages (as compared to EPS)		Chemicals	Fibres and dust	Non-renewable energy consumption **, MJ/FU	Renewable energy consumption, MJ/FU	Selected impacts (cradle-to-gate) (as compared to EPS) ****		
Flame retarded EPS sheets	-	-	Euroclass E Development of smoke and burning droplets	HBCCD is a PBT and POP substance - released during the use and disposal phase	No major issues	INC: 111 DEP: 185	INC: 1 DEP: 1		Recyclable - recycling increase the releases of HBCD to the environment	120-180 € per m^3 (excl. VAT)
Non- flame retarded EPS sheets	-	-	Euroclass F Development of smoke and burning droplets	No major issues	No major issues	INC: 111 DEP: 185	INC: 1 DEP: 1		Recyclable – slightly lower value of recycled materials	(≈)
Stone wool	Diffusion-open. Easier to fasten tight in some cases due to flexibility	Similar to or slightly lower insulation efficiency. Higher weight Lover compressive strength than some EPS types	Euroclass, A1,A2	Small releases of formaldehyde (CMR) from some types	Irritating fibres	INC: 139 DEP: 139	INC: 1 DEP: 1	Global warming (+) Acidification (+) Smog (÷)	Recyclable with low value of recycled materials	(≈/+)

Technical solution	Technical feasibility: Advantages (as compared to EPS)	Technical feasibility: Disadvantages (as compared to EPS)	Fire safety	Human health and ecotoxicological impacts: Chemicals	Human health and ecotoxicological impacts: Fibres and dust	Other environmental impacts and resource consumption: Non-renewable energy consumption **, MJ/FU	Other environmental impacts and resource consumption: Renewable energy consumption, MJ/FU	Other environmental impacts and resource consumption: Selected impacts (cradle-to-gate) (as compared to EPS) ****	Recyclability	Price of material (normalised to functional unit (FU) with similar insulation capacity)
Polyisocyanurate (PIR) sheets (flame retarded)	Higher insulation efficiency Higher compressive strength for some types		Euroclass E Development of smoke (less than EPS)	Halogenated phoshorous flame retardants in some types (not PBT or CMR) May be released during use and disposal	No major issues	INC: 119 DEP: 174	INC: 4 DEP: 4	Global warming (+) Acidification (+) Smog (÷)	Recyclable with low value of recycled materials - recycling may increase releases of halogenated phosphorus compounds	(≈/++)
Wood fibre insulation board	Diffusion-open	Slightly lower insulation efficiency. Somewhat vulnerable to moisture. Some qualities relatively heavy	Euroclass E, F Development of smoke	No major issues	No major issues	INC: -1 DEP: 201	INC: 544 DEP: 544	Global warming (÷) Acidification (+) Smog (÷)	Recyclable with low value of recycled materials	(+/++)
Cellular glass	Very high resistance to compression. Can reduce dimensions of a load bearing insulated wall in some cases. Insensitive to moisture and other climate and chemical pressures.	Slightly lower insulation efficiency Relatively heavy - if used for decks, roofs etc. It may in some cases warrant stronger dimensions of load bearing structures	Euroclass A1	No major issues	No major issues	INC: 166 DEP: 166	INC: 100 DEP: 100	Global warming (+) Acidification (+) Smog (÷)	Recyclable with low value of recycled materials	(++)

* Notation: (≈) prices typically similar to EPS; (+) 10-30% more than for EPS; (++) >30% more than EPS. Prices comparison based on materials meeting the functional unit.

** Primary energy consumption for the functional unit (FU) of 1 m^2 and a thermal resistance of 2.857 m^2·K/W. Covers manufacturing (cradle-to-gate) and disposal. For disposal two scenarios are assessed: INC, combustible materials are incinerated with energy recovery of 80% efficiency, DEP, all materials are deposited/landfilled.

*** Euroclasses: Se section 6.2. Range from the best A1:(non-combustible) to F: not tested (combustible)

***** Notation: (+) higher potential than EPS, (÷) lower potential than EPS

Sustainable use of insulation materials in buildings

A large potential for energy savings by improving the thermal insulation of buildings exist at the global scale. The energy savings and the environmental advantages are in general large compared with the energy consumption and environmental effects of the production, transport and use of insulation materials. Insulation may save up to 100 times more energy than the energy used for the manufacturing of the insulation materials.

The insulation material market is characterised by a range of materials, each with a niche defined by specific fire safety requirements, technical requirement, environmental requirements and price. The releases of HBCD, which have been identified to be a harmful substance of both local and global concern, however, makes the flame retarded EPS a less attractive material. Using a flame retardant with a better environmental profile than HBCD, flame retarded EPS could still be a cost-efficient, environmentally acceptable solution for many applications in the short term; in particular if recycled or disposed of for incineration with energy recovery after its use. Most developing countries do at the moment not have incineration plants with the technical efficiency that is required.

Today, still relatively small quantities of post-consumer insulation materials are disposed of and collection, and recycling systems are still to be developed in most countries. Efficient recycling or reuse of the foams would in particular be important for improving the lifecycle environmental profile of the foams. In some countries, the energy content of combustible insulation materials such as EPS is efficiently recovered by incineration, but in most countries this is not the situation. Recycling of the materials by the end of their service life generally improves the environmental performance of the materials in a life cycle perspective. But this does not apply to materials containing hazardous substances such as HBCD and the presence of the substance consequently counteract a more sustainable use of the EPS as no techniques are available at this moment which can be used to remove HBCD from the EPS foam.

The assessment does not indicate that any of the alternative materials have an outstanding environmental profile. For most of the types of insulation materials there seems to be differences among different brands and types as to the environmental and/or health profile of the materials. For all materials there is a potential for improving the environmental profile. For the stone wool as an example, the environmental and health profile can be improved by use of energy-efficient manufacturing process, use of renewable energy resources by the manufacturing, use of formaldehyde-free binders and use of fibres with less health impact (for some manufacturers some of this has been implemented already). For the foams, the use of blowing agent with no ozone layer depleting potential and low global warming potential has significantly improved the environmental profile. However, some XPS foams and spray PUR foams are still using blowing agents with a high global warming potential (Holladay, 2010; Wilson, 2010). Some of the halogenated flame retardants used in the PUR/PIR foams has raised some concerns, but non-halogenated flame retardants for these materials are marketed as well.

In the long term perspective, depletion of hydrocarbon resources may make plastic foams such as EPS and PUR less attractive, unless the raw materials can be produced from biomass e.g. by 2nd generation biofuel technologies using low-ranking biomass resources.

For less demanding applications such as cavity wall and loft insulation a wide range of natural fibre-based alternative materials exist and some of these may have a better environmental profile than the materials assessed here. Materials produced locally of natural fibre materials may be used in some areas of the world and may be produced with low energy consumption and low environmental impacts. However, these materials would not be typical alternatives to EPS for the more demanding applications concerned here.

The use of flame retardants is often a trade-off between higher fire safety and the possible impacts of the chemicals used. The development of less hazardous chemical flame retardants or non-chemical alternatives (alternative materials/product redesign) which do not compromise fire safety, would be an important step toward the use of more sustainable insulation materials.

An example of an initiative to develop more sustainable use of flame retardants is the Green Flame™ programme, hosted by SP Technical Research Institute of Sweden (Green flame, 2011). The initiative in a joint effort between authorities (National Association of State Fire Marshals (USA) and the Swedish Rescue Services Agency) and industry. The Green Flame™ is a programme that includes fire safety, health and environmental aspects in a single evaluation of any given product and the challenge accepted by the partnership is to move away from flame retardant chemicals posing unacceptable harm to the environment while maintaining a high level of fire protection through safe alternative chemicals and/or techniques. The intention is that the Green Flame™ system will provide competitive advantages to the companies that possess the competence and determination to develop consumer products that represent a major improvement in both fire safety and environmental quality.

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- EPS-Hartschaum (Styropor ®) für Wände und Dächer; IBU for Industrieverband Hartschaum e.V., 2009

- Factory-made Polyurethane Insulation Products; IBU for IVPU Industrieverband Polyurethan-Hartschaum e.V., 2010

- PAVATEX Holzfaserdämmplatten, IBU for PAVATEX SA, 2010

- FOAMGLAS®-Platten und FOAMGLAS®-Elemente, IBU for Pittsburgh Corning Europe NV, 2008

- Unkaschierte bzw. unbeschichtete kunstharzgebundene Steinwolle-Dämmstoffe; IBU for Deutsche Rockwool Mineralwoll GmbH & Co. OHG, 2008

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Annex 1:
Basic data from German Environmental Product Declarations

Data for the LCA part have been extracted from Umwelt-Deklarationen (EPD). Dämmstoffe. [German: Environmental Declarations (EPD). Insulation materials]. Institut Bauen und Umwelt e.V., Königswinter. Accessed May 2011 at: http://bau-umwelt.de/hp545/Daemmstoffe.htm?ITServ=CY77f4ba33X130164c2a16X36e0

The following basic data from the environmental declarations available at the website have been used in combination with the information on the density and thermal conductivity of the materials:

EPS. EPS-Hartschaum (Styropor ®) für Wände und Dächer; IBU for Industrieverband Hartschaum e.V., 2009

EPS-Hartschaum für Wände und Dächer (Herstellung + End of Life)		
Auswertegröße in Einheit pro m³	**W/D-035**	**W/D-040**
Primärenergie, nicht erneuerbar [MJ]	1145,2	868,0
Primärenergie, erneuerbar [MJ]	1,0	1,7
Abiotischer Ressourcenverbrauch [kg Sb-Äqv.]	5,5E-01	4,2E-01
Treibhauspotenzial (GWP) [kg CO_2-Äqv.]	8,9E+01	6,7E+01
Ozonabbaupotenzial (ODP) [kg R11-Äqv.]	-1,8E-07	2,8E-08
Versauerungspotenzial (AP) [kg SO_2-Äqv.]	8,9E-02	6,7E-02
Eutrophierungspotenzial (EP) [kg PO_4^{3-}-Äqv.]	9,4E-03	7,1E-03
Sommersmogpotenzial (POCP) [kg C_2H_4-Äqv.]	3,5E-01	3,0E-01

Produktuntergruppe Wand/Dach-035					
Größe	**Einheit pro m³**	**Total**	**Herstel-lung**	**Trans-port**	**End-of-Life**
ADP	[kg Sb-Äqv.]	5,5E-01	8,5E-01	1,4E-03	-3,0E-01
GWP	[kg CO2-Äqv.]	8,9E+01	6,2E+01	2,2E-01	2,7E+01
ODP	[kg R11-Äqv.]	-1,8E-07[3]	1,7E-06	3,6E-10	-1,9E-06
AP	[kg SO2-Äqv.]	8,9E-02	1,3E-01	1,3E-03	-4,5E-02
EP	[kg PO4-Äqv.]	9,4E-03	1,3E-02	2,2E-04	-4,3E-03
POCP	[kg Ethen-Äqv.]	3,5E-01	3,5E-01	9,5E-05	-4,0E-03

Produktuntergruppe Wand/Dach-040					
Größe	**Einheit pro m³**	**Total**	**Herstel-lung**	**Trans-port**	**End-of-Life**
ADP	[kg Sb-Äqv.]	4,2E-01	6,4E-01	1,1E-03	-2,2E-01
GWP	[kg CO2-Äqv.]	6,7E+01	4,7E+01	1,6E-01	2,0E+01
ODP	[kg R11-Äqv.]	2,8E-08	1,4E-06	2,7E-10	-1,4E-06
AP	[kg SO2-Äqv.]	6,7E-02	1,0E-01	9,5E-04	-3,4E-02
EP	[kg PO4-Äqv.]	7,1E-03	1,0E-02	1,6E-04	-3,2E-03
POCP	[kg Ethen-Äqv.]	3,0E-01	3,0E-01	7,2E-05	-3,0E-03

Factory-made Polyurethane Insulation Products; IBU for IVPU Industrieverband Polyurethan-Hartschaum e.V., 2010

Polyurethane insulation panels (manufacture)									
	Polyurethane block WLS 030 (manufacture + end of life)			Polyurethane WLS 028 mineral fleece (manufacture + end of life)			Polyurethane WLS 024 alu (manufacture + end of life)		
Evaluation factor in units per m³	TOTAL	Manufacture (incl. transport)	EOL	TOTAL	Manufacture (incl. transport)	EOL	TOTAL	Manufacture (incl. transport)	EOL
Non-regenerative primary energy [MJ]	2269	2768	-499	2263.2	2773.2	-510	2424.53	2928.53	-504
Regenerative primary energy [MJ]	43.27	48.89	-5.62	42.14	47.84	-5.7	86.89	92.55	-5.66
Greenhouse warming potential (GWP 100) [kg CO2 equiv.]	191.54	134.03	57.51	194.64	135.12	59.52	205.63	147.07	58.56
Ozone depletion potential (ODP) [kg R11 equiv.]	1.02E-06	2.19E-06	-1.17E-06	7.70E-07	1.96E-06	-1.19E-06	1.98E-06	3.16E-06	-1.18E-06
Acidification potential (AP) [kg SO_2 equiv.]	0.4284	0.425	0.0034	0.465	0.429	0.036	0.546	0.511	0.035
Eutrophication potential (EP) [kg PO_4 equiv.]	0.054	0.044	9.70E-03	0.054	0.044	1.01E-02	0.056	0.046	9.90E-03
Summer smog potential (POCP) [kg C_2H_4 equiv.]	0.071	0.071	1.99E-04	0.074	0.074	2.66E-04	0.079	0.079	2.34E-04

PAVATEX Holzfaserdämmplatten, IBU for PAVATEX SA, 2010

		PAVATHERM			PAVATHERM PLUS⁺		
pro m³		Herstellung	Entsorgung	Total	Herstellung	Entsorgung	Total
Primärenergie nicht-erneuerbar	MJ	1341	-3214	-1872	1647	-3933	-2286
Primärenergie erneuerbar	MJ	3601	-90	3512	4553	-110	4443
Treibhauspotential (GWP)	kg CO_2 eq	-181	71	-110	-220	88	-132
Ozonabbaupotential (ODP)	kg CFC-11 eq	5.96E-06	-2.04E-05	-1.45E-05	6.93E-06	-2.52E-05	-1.83E-05
Versauerungspotential (AP)	kg SO_2 eq	0.192	-0.147	0.044	0.274	-0.182	0.093
Überdüngungspotential (NP)	kg PO_4^{3-} eq	0.072	-0.013	0.059	0.094	-0.015	0.079
Ozonbildungspotential (POCP)	kg C_2H_4	1.29E-02	-1.25E-02	3.16E-04	1.73E-02	-1.55E-02	1.85E-03
		ISOROOF NATUR/ISOLAIR			DIFFUTHERM		
pro m³		Herstellung	Entsorgung	Total	Herstellung	Entsorgung	Total
Primärenergie nicht-erneuerbar	MJ	2764	-5592	-2828	1718	-4132	-2414
Primärenergie erneuerbar	MJ	6184	-156	6028	4644	-115	4528
Treibhauspotential (GWP)	kg CO_2 eq	-285	125	-160	-233	91	-142
Ozonabbaupotential (ODP)	kg CFC-11 eq	1.15E-05	-3.55E-05	-2.41E-05	7.63E-06	-2.63E-05	-1.86E-05
Versauerungspotential (AP)	kg SO_2 eq	0.503	-0.257	0.246	0.247	-0.189	0.057
Überdüngungspotential (NP)	kg PO_4^{3-} eq	0.131	-0.020	0.111	0.093	-0.016	0.076
Ozonbildungspotential (POCP)	kg C_2H_4	2.78E-02	-2.18E-02	5.91E-03	1.66E-02	-1.61E-02	4.41E-04

FOAMGLAS®-Platten und FOAMGLAS®-Elemente, IBU for Pittsburgh Corning Europe NV, 2008

FOAMGLAS®-Platten und –Elemente (Rohstoffe u. Herstellung)

Ergebnisse: W+F (100 kg/m³) und Perinsul High Grade (200 kg/m³)	Einheit	W+F pro m³	Perinsul HG pro m³	W+F pro kg	Perinsul HG pro kg	W+F R=2m²K/W pro m²	Perinsul HG R=2m²K/W pro m²
PE, nicht erneuerbar	[MJ]	1525,9	3049,22	15,26	15,25	115,97	335,41
PE, erneuerbar	[MJ]	920,6	1725,24	9,21	8,63	69,97	189,78
PE, nicht erneuerbar	[kWh]	423,9	847,0	4,24	4,24	32,21	93,17
PE, erneuerbar	[kWh]	255,7	479,2	2,56	2,40	19,43	52,72
Treibhauspotenzial (GWP)	[kg CO_2-Äqv.]	109,23	212,22	1,09	1,06	8,30	23,34
Ozonabbaupotenzial (ODP)	[kg R11- Äqv.]	$0,74 \cdot 10^{-6}$	$1,72 \cdot 10^{-6}$	$7,40 \cdot 10^{-9}$	$8,60 \cdot 10^{-9}$	$56,2 \cdot 10^{-9}$	$0,19 \cdot 10^{-6}$
Versauerungspotenzial (AP)	[kg SO_2- Äqv.]	0,208	0,411	$2,08 \cdot 10^{-3}$	$2,06 \cdot 10^{-3}$	0,016	0,045
Eutrophierungspoten-zial (EP)	[kg PO_4^{3-}- Äqv.]	0,023	0,046	$0,23 \cdot 10^{-3}$	$0,23 \cdot 10^{-3}$	$1,75 \cdot 10^{-3}$	$5,06 \cdot 10^{-3}$
Sommersmog (POCP)	[kg Ethen- Äqv.]	0,019	0,036	$0,19 \cdot 10^{-3}$	$0,18 \cdot 10^{-3}$	$1,44 \cdot 10^{-3}$	$3,96 \cdot 10^{-3}$

Unkaschierte bzw. unbeschichtete kunstharzgebundene Steinwolle-Dämmstoffe; IBU for Deutsche Rockwool Mineralwoll GmbH & Co. OHG, 2008

Auswertegröße	Einheit pro kg Steinwolle	Herstellung von Steinwolle unkaschiert
Primärenergie nicht erneuerbar	[MJ]	12,9
Primärenergie erneuerbar	[MJ]	0,1
Treibhauspotenzial (GWP 100)	[kg CO_2-Äqv.]	1,16
Ozonabbaupotenzial (ODP)	[kg R11-Äqv.]	$8,5 * 10^{-8}$
Versauerungspotential (AP)	[kg SO_2-Äqv.]	$7,5 * 10^{-3}$
Überdüngungspotential (EP)	[kg Phosphat-Äqv.]	$8,3 * 10^{-4}$
Sommersmogpotential (POCP)	[kg Ethen-Äqv.]	$5,2 * 10^{-4}$

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Tittel - norsk og engelsk
Alternativer til bruk av flammehemmet EPS i bygninger
Alternatives to the use of flame retarded EPS in buildings

Sammendrag – summary

Undersøkelsen har evaluert utvalgte alternativer til flammehemmet EPS brukt som isolasjonsmateriale i bygninger. EPS er flammehemmet med miljøgiften HBCD. Materialene er blitt vurdert med hensyn til deres tekniske egenskaper, brannsikkerhet, miljø- og sunnhetsprofil og pris. For samtlige av de undersøkte anvendelsene av EPS, markedsføres det i dag alternative isoleringsmaterialer. Prisen for de rimeligste alternativene varierer fra mer eller mindre det samme som EPS til omkring 30% mer avhengig av anvendelsesområde.

The current study evaluates selected alternatives to EPS insulation materials used in the building sector. EPS is flamer retarded with the hazardous chemical HBCD. The materials are evaluated as to their technical properties, fire safety performance, environmental and health profile, and price. For all the concerned application of EPS, alternative insulation materials are marketed today. The price of the cheapest alternatives ranges from more or less the same price as for flame retarded EPS to approximately 30% more depending on application.

4 emneord	4 subject words
HBCD, HBCDD, POP, prioritert miljøgift	HBCD, HBCDD, POP, priority substance

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Climate and Pollution Agency

The Climate and Pollution Agency reports to the Ministry of the Environment and has 325 employees, based mainly in Oslo. We implement government policy on pollution. We act as advisors, guardians and stewards for the environment. Our most important fields of work include climate change, chemicals, marine and freshwater environment, waste management, air quality and noise. Our vision is a future without pollution.
We are working to

- reduce greenhouse gas emissions
- reduce the spread of hazardous substances harmful to health and the environment
- achieve integrated and ecosystem-based management of the marine and freshwater environment
- increase waste recovery and reduce emissions from waste
- reduce the harmful effects of air pollution and noise

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