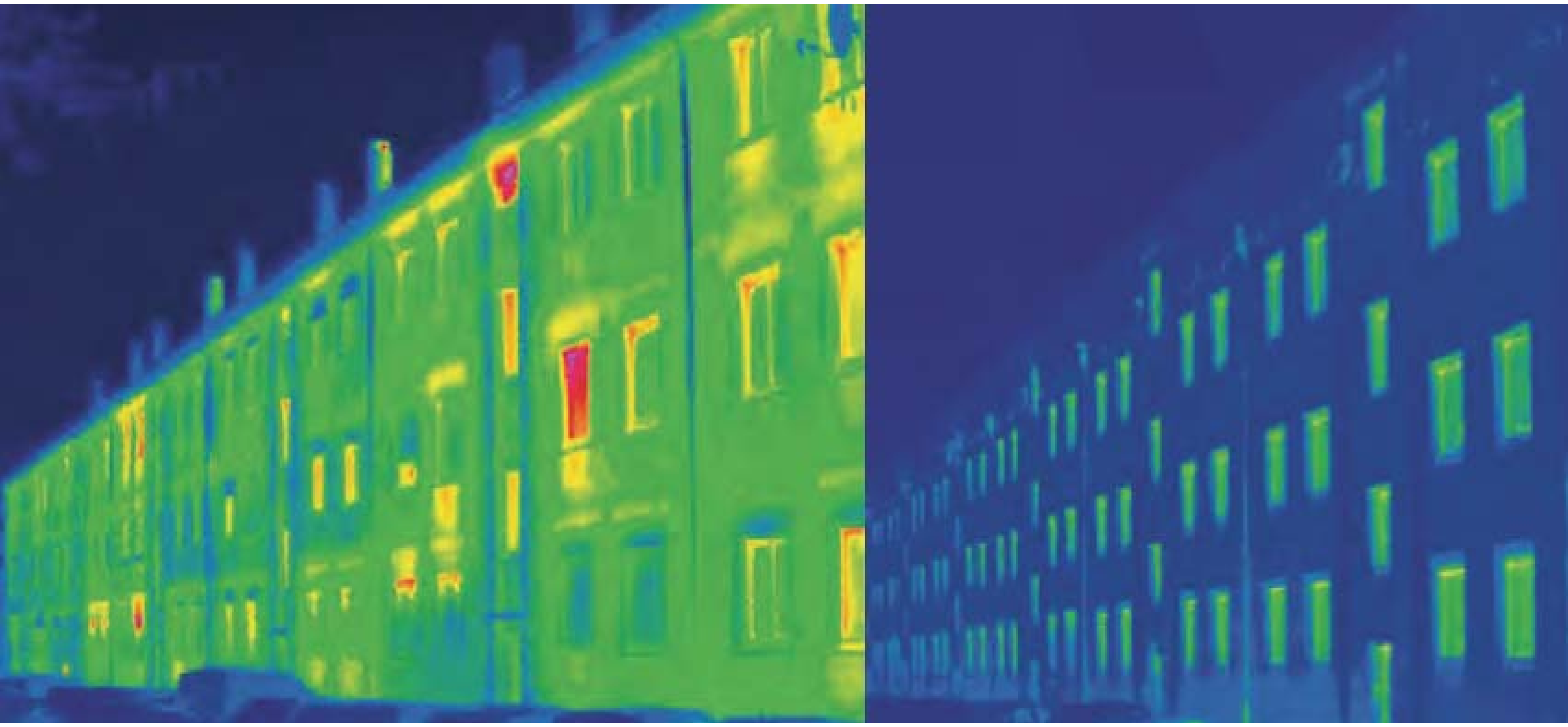
Master thesis report:

Comparative assessment of insulating materials on technical, environmental and health aspects for application in building renovation to the Passive house level



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List of abbreviations

Abbreviations used in eqations

Rc - Thermal resistance of a construction [m^2·K/W]
λ - Thermal conductivity [W/m·K]
μ - Water vapour diffusion resistance factor [-]
k - Heat transmission coefficient ($1/R_c$) [W/m^2·K]
EPC - Energy performance coefficient [-]

Insulating materials

EPS – Expanded polystyrene
UF – Ureaformaldehyde foam
PF – Phenon formaldehyde
PIR - Polyisocyanurathe
PLA – Polylactic Acid
PUR – Polyurethane
XPS – Extruded polystyrene

Others

CED - Cumulative energy demand
EPD - Environmental product declaration
GHG - Greenhouse gas
GWP - Global warming potential
HBCD - Hexabromocyclododecane
IBU - Institut Bauen Und Umwelt
LCA - Life cycle analysis
ODP - Ozone depletion potential

Preface

This thesis could not have been what it is now without the help and knowledge of the following people:
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Special thanks go out to Dr. Martin Patel, for his critical review and questions during this thesis period, even in the weekends.

Summary

Over the last 30 years, the requirements for the thermal insulation of buildings in the Netherlands have been increased. In 2006, the primary energy demand for space heating was 660 PJ. The fact that this 660 PJ is approximately 20% of the total Dutch primary energy use strongly indicates the importance of improved thermal insulation of the existing building stock. Insulating an existing building with thermal insulation can be complex, costly and time consuming. During a building renovation or refurbishment, the applied thermal insulation must provide a high level of thermal resistances to the building envelope, in order to lower the energy demand for space heat as far as possible.

The Passive house concept defines such levels of insulation for both new and existing buildings, resulting in thick layers of insulating materials. The Passive house concept is an integral concept in which next to thermal insulation, also ventilation standards are prescribed with which a solid basis is laid for energy efficient building renovations. Before the Passive house concept is used on a large scale, the technical, environmental and health aspects of the insulating materials used within the concept must be investigated.

The main research question therefore is:

> "W*hich insulating materials are most suitable to reach the energy efficiency level of a Passive house, when taking technical, environmental and health aspects into account?"*

By means of interviews with producers and experts in the field, literature research and a quantitative assessment of LCA studies, it was found that glass- and rock wool (mineral wool) together with Expanded Polystyrene (EPS) are the most suitable insulating materials for application within Passive house renovation. This is because of the fact that for both mineral wool (glass wool and rock wool) and EPS, multiple end-of-life scenarios are available. EPS can be recycled or incinerated, whereas mineral wools can be recycled into new mineral wool, but also into other products such as facade panels or sound insulation. For both EPS and mineral wool recycling facilities are already in place and used in practice. Materials such as PUR/PIR and PF-foam do not have these recycling options yet, which only leaves incineration as the end-of-life solution. In the study also hemp- and flax wool were examined. It turns out that the environmental impact of these materials is often higher than that of EPS and mineral wool. Additionally, the use of polyester support fibres in hemp- and flax wool makes it impossible to recycle these fibres, leaving incineration as the only end-of-life option. From a health point of view, both EPS and mineral wools should be improved further. Especially the formaldehyde based binders used in mineral wool and the fire retardant hexabromocyclododecane used in EPS should be replaced by other materials on a short term. The developments thereof are already in progress and in an advanced phase.

Besides the LCA assessment, two other quantitative assessments were made. The focus of both assessments was the insulation of existing cavity walls. The first assessment provides insight into the amount of insulating material needed for both normal and Passive house renovation. The second assessment estimates the savings of insulating empty cavity walls. The results of this assessment show that filling the empty cavity walls in the Netherlands would require approximately 10 million m^3 of insulating materials versus 54 million m^3 for renovation to the Passive house level. The estimated savings of insulating the existing empty cavity walls by filling the air cavity, is about 69 PJ/year which annually avoids the emission of 3.9 $GtCO_2$ –eq. If the cavity wall would be renovated to a Passive house level, the savings and avoided emissions would be 96 PJ/year and 5.3$GtCO_2$ eq. In this estimation, the energy and GHG-emissions of the insulating materials are discounted over a lifetime of 50 years. The emissions and energy use during the renovation could not be taken into account, because data thereof was not available. Overall, the emissions and energy use of the insulating materials is compensated within a year by the emission reduction and energy savings of insulation the existing walls.

1 Introduction

Over the last thirty years, the Dutch government has been promoting thermal insulation. This promotion started in the year 1978 with the introduction of the ‘national insulation programme’. Buildings constructed before 1978 had not been subjected to any regulation regarding insulation and were therefore not fitted with insulating materials. The goal of the national insulation programme was to have 2.5 million houses (54% of the 1978’s residential building stock) retrofitted with insulating material, to decrease their total natural gas usage by 1.6 billion m^3/year (Entrop and Brouwers, 2007a). This is equivalent to a 14% reduction of the natural gas consumption by households in 1978 (Entrop and Brouwers, 2007b). In succession to the national insulation programme, the Dutch government introduced the ‘energy performance standard’ in 1995. Apart from other requirements, the energy performance standard requires the building envelope (roof, walls and floor) to be constructed with a thermal resistance of at least 2.5 $m^2 \cdot K/W$. This requirement is also recorded into the 2003 building decree (Bouwbesluit, 2003). In 2012, the newly revisited building decree will come into effect, in which the thermal resistance standard for the building envelope will be raised to 3.5 $m^2 \cdot K/W$ (Concept Bouwbesluit 2012, 2011).

These new requirements are needed to lower the amount of energy needed for space heating. The primary energy needed for space heating in both utility buildings and households was approximately 660 PJ in 2006 (Menkveld and Beurskens, 2009). This accounts for 20% of the total primary energy consumption in the Netherlands, which was 3233 PJ in 2006 (Statistics Netherlands, 2011a). Since the existing buildings in the Netherlands already account for 20% of the total domestic primary energy use, the focus of this research is on insulating materials for existing buildings.

During the design and construction of new buildings, insulation solutions can be incorporated. For existing buildings however, the options for insulating existing structures are limited (Jeeninga and Volkers, 2003). Renovating or refurbishing a building can be complex, costly and time consuming. Because of this, it is necessary to insulate these buildings to a high standard, or at least the minimum standard set by the building decree. However, considering the fact that the theoretical lifetime of a house is 50 years, insulating to a higher standard is preferable.

One way of ensuring a high standard of insulation is the Passive house concept. Passive houses are insulated in such a way, that the maximum amount of energy needed for space heating is no more than 15 kWh/m^2a for new buildings and 25 kWh/m^2a for renovations. The building envelope of the building must have a thermal resistance of at least 6.5 m^2K/W (De Boer et al, 2009). Insulating a building to such an energy level with a commonly used insulating material such as mineral wool, requires a building envelope with an insulation layer of up to 300 mm (Passipedia, 2011).

Before using such large quantities of insulating materials, the environmental and health impacts of the different materials must be known. These impacts are investigated for the production, use and waste phase of the materials so that future problems with these materials can be foreseen and avoided. Against this background it is one of the objectives of this study to provide an overview of different insulating materials currently available. In a subsequent step, the environmental impacts of the entire life cycle of different materials are assessed. To get an impression of the renovating potential and the amount of insulating material needed in the Netherlands, an estimation is made based on un-insulated cavity walls. On top of this, the CO_2 and energy saving potential are estimated based upon insulating the empty cavity wall volume in the Netherlands for both common and Passive house renovation.

1.1 Research question

When the aspects mentioned above are combined, the following research question can be posed:

> "W*hich insulating materials are most suitable to reach the energy efficiency level of a Passive house, when taking technical, environmental and health aspects into account?"*

To answer the research question posed above, answers are needed to the following sub-questions:

1. *Which buildings methods are commonly applied to insulate the building envelope?*

The answer to this question gives insight into the different methods of constructing a building envelope commonly used in the Netherlands. The different construction methods could require different types of insulating materials. Understanding the difference between the different types of building envelopes provides insight in the practical application of different types of insulating materials.

2. *What are the important properties for insulating materials?*

This question is aimed at finding the important properties of insulating materials. A comparison between insulating materials should be based on its most important properties.

3. *What are the commonly used or new (high-tech) insulating materials?*

For this sub question the research will focus on the properties and practical application of insulating materials that are currently on the market, but also on materials that are not yet market ready, but could become so in the near future. New materials could have a higher thermal resistance than the already existing materials, which could reduce the thickness of the insulating layer. For the common materials the market share is also looked into.

4. *How do the new and commonly used insulating materials perform from a technical, environmental and health point of view?*

The following technical aspects will be considered: thermal conductivity, density, water vapour resistance, fire resistance, practical application, and any other material specific aspects. From an environmental point of view the following aspects are considered: energy for production e.g. energy/kg material, end-of-life options (waste phase) e.g. incineration, re-use/recycle or landfill. The life cycle of the materials should be clear from cradle-to-grave. Other environmental aspects that must be taken into account are: greenhouse gas and other gaseous or particle emissions. Also other aspect that might be important for specific materials such as health issues are taken into account.

5. *What are the requirements for renovating a building to the Passive house level?*

To renovate to the Passive house level requires a thorough understanding of its criteria. These criteria must be known for both new as well as existing buildings.

6. *What are the practical differences between insulating according to the building decree and the Passive house level of insulation?*

An assessment should be made of the practical differences (e.g. manner of ventilation, air tightness, energy demand) between insulating according to the 2003 building decree and insulating according to the Passive house level of insulation.

7. *What savings can be achieved by insulation and how much insulating material does this require?*

This questions aims at estimating the amount of material that is needed for the insulation of existing buildings in the Netherlands and the saving potential thereof.

8. *Which insulation materials can best be used during the renovation of a building, taking into account the aspects of the previous sub questions and the level of insulation of the Passive house concept?*

With the technical, environmental and health aspects found for the different materials and the Passive house requirements, the best suited materials can be identified.

1.2 Methodology

The information required to answer the main and sub research questions was collected by means of:

- Literature research
- Expert interviews
- Quantitative assessments

Literature research

A wide variety of literature was consulted, ranging from academic literature to product leaflets from producers and suppliers. Building decrees and other regulations were also of importance, since buildings have to meet certain legal requirements. Academic literature was consulted to find information considering the environmental, health and technical aspects of the insulating materials.

Producers of insulating materials also provided such information. Literature of several independent sources such as the Dutch Institute for building biology and ecology (NIBE) and the German Institute for construction and the environment (IBU) was used to find life cycle data and health aspects for insulating materials. The information from both the producers and the independent sources are compared to see what differences between the values occur and what could be an explanation for these differences. Technical information was obtained from the producers of insulating materials and textbooks on construction. Governmental studies were used to find information on the current state of insulation of the existing building stock and its energy use.

Expert interviews

During the research, producers of insulating materials were interviewed in order to obtain data and products specific aspects which are hard to find in literature (alternative recycling options, or other developments). Next to producers, also other experts from different sectors were interviewed. The in dept knowledge of the interviewed experts provided valuable insight into the practical problems of renovation.

Below is a list of expert institutes and companies which were interviewed during the research:

- Producers of insulating materials:
    - Kingspan (PF-foam, PIR)
    - Knauf (Wood wool, Glass wool, Rock wool, EPS)
    - Isover (Glass wool)
    - Rockwool (Rock wool)
    - Isobouw (EPS, Expanded PLA)
- Dutch Passive house foundation (Stichting Passiefbouwen)
- Social housing corporation Aramis (Passive renovation of 246 houses)
- BAM (Passive renovation of 14 apartments with protected cityscape)
- EUMEPS (European branch organization for EPS producers)

Apart from the interviews, the producers of insulating materials were also contacted for further details about their products. NIBE did not take part in an interview, but was often contacted for explanation of their research methods and the results thereof.

Own quantitative assessment

In order to compare the data obtained from the different sources, a functional unit is defined which is used as the basis of the assessment. As a functional unit, a cavity wall was chosen with a thermal resistance of 3.5 $m^2 \cdot K/W$. This functional unit is also used in the calculation of the price of the different insulating materials. Furthermore, the functional unit is used to allow for a fair comparison: all life cycle analysis (LCA) data is converted to the functional unit. In addition, a separation is made between cradle-to-gate and cradle-to-grave analyses. Next to this, an estimation is made of the renovation potential of cavity wall insulation in the Netherlands. This estimation is based on two studies by the Dutch ministry of public housing, environmental planning and environmental management (VROM). In these studies, a reflection is given of the amount and types of houses together with their grade of insulation (VROM, 2009). By combining the results from these studies an estimation of the renovation potential and the amount of insulating material needed for the insulation of empty cavity walls in the Netherlands is obtained. The results from the LCA assessment and the estimation are combined to investigate the impact of the products in relation to the saving potential.

Boundaries

The focus of this thesis lies on insulating materials for the building envelope of buildings. The building envelope covers walls, roofs and floors. In this thesis, the focus will be lied on wall insulation, because walls represent the largest surface of a building. Doors and windows are not insulated with the type of insulating materials important for this thesis and will therefore receive little attention. Buildings of interest are existing residential buildings. The outcome of the research should be applicable to such buildings.

1.3 Structure of the report

The first sub-research question is used to obtain an understanding of the Dutch methods of constructing the building envelope. An overview thereof is provided in appendix A. In appendix B an extensive summary can be found of both common and new technology insulating materials. From this summary, two overviews are distilled that form the answer to sub-research questions 2 and 3 and cover the technical aspects of sub-question 4. The overviews can be found in section 2.1. From section 2.2 onwards, different LCA datasets are assessed to find the environmental aspects from sub-question 4. Section 2.7 deals with the different end-of-life options of insulating materials, whereas section 2.8 elaborates on the health aspects from sub-question 4. The requirements for renovating to the Passive house level and the differences between the Passive house requirements and the building decree can be found in section 3.4. These requirements result in an estimation for the amount of insulating material needed for Passive house renovation (section 3.6.4). In chapter 4 the two assessments mentioned above are combined, after which in chapter 5 an answer is formulated to sub-research question 8 and the main research question.

2 Life cycle assessment of insulating materials

This section focuses on the comparative assessment of life cycle analyses (LCA) of different insulating materials. The goal of the assessment is finding the differences between the environmental, technical and health aspects of insulating materials by assessing multiple LCA studies. To do so, first an overview is created of the insulating materials that are currently on the market and the properties thereof. With this overview, a selection of materials will be made for which an assessment of different LCA studies will be done. To demarcate the materials for the LCA, the focus will lie on materials suitable for cavity wall constructions, since cavity walls are a common element of both existing and newly built houses (VROM, 2009).

2.1 Properties of insulating materials

For a material to be considered an insulating material, it must hold certain properties. Four important properties for insulating materials are listed below. In appendix B, these properties are explained in detail.

1. **Thermal conductivity (λ)**

The raison d'être of insulating materials is their thermal conductivity. Because of the low thermal conductivity of insulating materials, the heat flow through the materials is limited. The unit of the thermal conductivity is W/m·K. The thermal conductivity of an insulating material is of great influence on the total thermal resistance of a construction (R_c). This is explained in detail in appendix B.

2. **Density**

A factor that is of influence on the thermal conductivity of a material is the density of a material. A lower density means that there is less material which can conduct heat, resulting in more air or gas to resist the heat flow. However, for certain purposes like flat roofs or cavity walls, self supporting materials or materials with a high compressive strength are needed. This can only be achieved by a more dense material structure. Overall, a denser structure results in a higher thermal conductivity.

3. **Water vapour diffusion resistance (µ)**

When the building envelope of a building is insulated, moisture problems must be avoided. These problems are the result of condensing water vapour and can lead to structural damage (rotting of wood), cold bridges or wet spots that form a breeding place for mould. If warm air with a high humidity diffuses from the inside of a building to the colder outside, the water vapour could condense within the insulating material. This diffusion of warm water vapour to the less humid outside environment occurs because of a difference in vapour pressure. The vapour pressure inside the building is higher than the vapour pressure outside. By the diffusion of water vapour from the high to the low pressure, this unbalance is cancelled out. The high humidity inside buildings is due to the users of the building: cooking, showering, plants and the water vapour exhaled by humans, contribute to an increasing humidity (Van den Hout et al, 2005).

The µ value of an insulating material gives the relation between how much water vapour diffuses through a layer of air, and a layer of material of the same thickness:

$$\mu = \frac{\text{vapour diffusion resistance of a material with thickness d}}{\text{vapour diffusion resistance of an air layer with thickness d}}$$

µ is therefore a useful indicator for insulating materials, because it provides a good first impression of a materials vapour diffusion resistance, which can be of influence on its practical application.

4. Resistance to fire (fire class)

Thermal insulating materials must have a fire classification. This classification is important because of its influence on the application of insulating materials. A fire classification is part of the CE-marking that all construction materials are obliged to have (Bouwbesluit, 2003c). The classification is prescribed in the European norm EN-13501-1. In the norm, seven main classes are specified: A1, A2, B, C, D, E and F, in which A1 is non-flammable and E is highly flammable. If a product has no specification, or is extremely flammable, it will receive class F. Besides the main classes, there are two other classes: smoke growth rate (s1, s2 or s3) and flaming droplets or particles (d0, d1 or d2) (NEN-13501-1, 2009). During this research, only the main classes will be reported (A1, A2, B etc.), because the latter two classes are more product specific than material specific. Next to that, it is the entire construction that is assessed for its fire class, not the separate materials. Materials with a low fire class of for instance E or F, can still be used within a construction, as long as the required classification for the entire construction is achieved. However, although the requirements differ per construction and residential function, the minimal classification is D, with smoke class s2. For flaming droplets, there is no requirement in the Dutch building decree (Staatscourant, 2005).

5. Price

Perhaps the most important factor in practice is the price of insulating materials. For the determination of the prices, the price of insulating a cavity wall to a certain thermal resistance will be determined. This is done per material, so that insight is provided in both the practical applications as well as the costs.

2.1.1 Categories of insulating materials

To compare the insulating materials, a division is made by setting up material categories. According to Papadopoulus (2005, pp. 79) four categories can be defined that are based on the chemical composition of the base material from which the insulating material is produced. These four main categories are:

1. Inorganic materials
2. Organic materials
3. Combined materials
4. New technology materials

For this research, the third category 'combined materials' is not used, because it lists insulating materials that consist out of multiple materials (e.g. foam with plasterboard). Since the focus lies on commonly used and new insulating materials, the fourth category is used, together with category one and two from the above list. This allows both new (high-tech) and commonly used materials to be divided into categories easily.

The three categories that remain are still very general and should be more detailed. To do so, the organic materials are split into two groups: materials made from a petrochemical base (e.g. polymers like polystyrene, polyisocyanurate) and materials made from renewable resources (e.g. sheep wool, flax). This separation is useful, because the renewable materials are not common materials yet, but might become so. The inorganic insulating materials have a mineral base material (e.g. cullet or basalt) (VIBE, 2007). Another division that can be made according to Papadopoulus is the structure of the materials (e.g. foamy, fibrous). This division does not cover all materials. Calcium Silicate for instance, is a material that is inorganic, not fibrous, but also not foamy. Therefore the category 'cellular' is used (Al-Homoud, 2005). Since the structure of the material could be of importance for its practical application, this division is made as well. The organization chart in figure 2.1.1 shows the classification scheme that is derived from both Papadopoulos and Al-Homoud. No fibrous petrochemical materials were encountered during the search for materials, therefore the category 'fibrous' is left out.

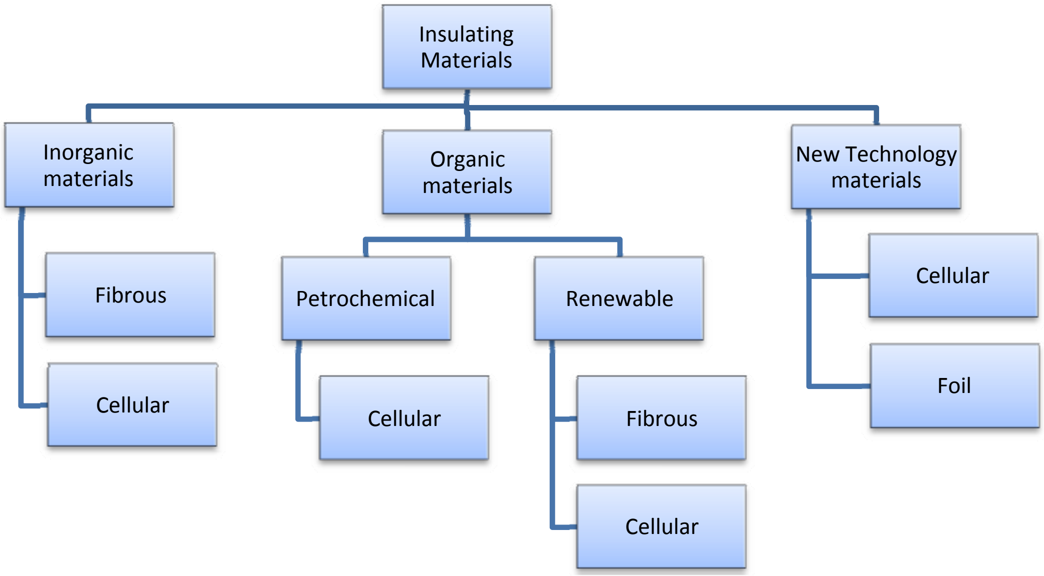

figure 2.1.1 categorization of insulating materials

Categorizing the insulating materials allows a conveniently arranged overview to be created. Based on the division of materials as showed in figure 2.1.1, two overviews are created of commonly used and new technology insulation materials. The first overview (table 2.1) presents all the materials with the properties described in the previous section. The second overview (table 2.2) shows the practical application options of the different product varieties of insulating materials. For the complete overview and explanation of different materials and their production process, see appendix B. For an overview of common methods used to construct the building envelope of a building, see appendix A.

table 2.1 overview of insulating materials and their properties

Material	Base materials	Thermal Conductivity (λ) [W/m·K]	Density [kg/m^3]	Fire Class NEN-EN13501	Water vapour resistance factor (μ) [-]	Price when used in R_c=3.5 cavity wall [€/m^2]	Flocks	Panels	Rolls	Injectable foam	Granules
Inorganic: fibrous											
Glass wool	Cullet, quartz sand, dolomite	0.030-0.040	12-150	A1	≥1	9.30-14.70	X	X	X	-	-
Rock wool	Diabase, basalt	0.030-0.040	25-200	A1	1-5	12.25-20.05	X	X	X	-	-
Inorganic: cellular											
Calcium Silicate	Chalk, sand, cellulose fibres	0.059-0.065	200-240	A1	6-20	-	-	X	-	-	-
Foam glass	Cullet, feldspar, dolomite	0.038-0.055	100-200	A1	∞	46.46-62.37	-	X	-	-	-
Perlite	Silicon dioxide, aluminium oxide	0.040-0.060	32-176	A1	3-5	38.25-42.41	-	X	-	-	X
Vermiculite	Magnesium-aluminium silicate	0.040-0.064	64-130	A1	3-5	-	-	X	-	-	X
Organic-petrochemical: cellular											
Expanded polystyrene (EPS)	Benzene, ethylene, pentane	0.032-0.045	10-80	E-F	20-100	8.60-17.35	-	X	-	-	X
Extruded polystyrene (XPS)	Benzene, ethylene, pentane	0.025-0.040	15-85	E-F	80-300	18.00-23.10	-	X	-	-	-
Phenol formaldehyde (PF)	Phenol, formaldehyde	0.020-0.021	35-40	B-D	30-50	23.00	-	X	-	-	-
Polyurethane (PUR)	Isocyanate, (polyether)polyol	0.022-0.035	30-160	D-F	50-100	24.91	-	X	-	X	-
Polyisocyanurate (PIR)	Polyester polyol, MDI	0.020-0.035	28-40	D-F	50-100	20.51-23.50	-	X	-	-	-
Urea formaldehyde (UF)	Urea formaldehyde	0.045	15	D-E	1.5-2.4	-	-	-	-	X	-
Organic – renewable: fibrous											
Cellulose (paper wool)	Recycled paper, wood fibre	0.038-0.040	30-70	E	2-3	24.60	X	X	-	-	-
Coconut	Coconut fibres	0.040-0.045	140	E	1-10	84.35	-	X	-	-	-
Flax (flax wool)	Flax fibres, support fibres	0.035-0.040	28	C	1-2	15.18	-	X	X	-	-
Hemp (hemp wool)	Hemp fibres, support fibres	0.038-0.040	30-42	E	1-2	15.13-19.45	-	X	X	-	-
Recycled cotton	Recycled clothing, support	0.038	18	E	1-5	19.32	X	X	X	-	-
Sheep wool	Sheep wool, support fibres	0.035-0.40	25-60	E	1-2	24.00	-	X	X	-	-
Wood wool	Waste wood or virgin wood	0.038-0.058	55-140	E	5	26.60-37.83	-	X	-	-	-
Organic – renewable: cellular											
Expanded cork	Cork oak bark	0.037-0.043	100-120	E	5-30	25.58-44.68	-	X	-	-	X
New technology materials: foil											
Thermosheets	Polyester, aluminium	0.038-0.045	17g/m^2	F	68,000	-	-	-	X	-	-
Thermos cushions	Polyester, aluminium	0.038-0.045	17g/m^2	F	68,000	-	-	-	X	-	-
New technology materials: cellular											
Aerogel	Silicon alkoxide	0.013-0.021	100-150	A1	2-5.5	61.50-111.12	-	-	X	-	X
Expanded polylactic acid	Sugarcane, cassava	0.034	35	E-F	20-100	-	-	X	-	-	X
Vacuum insulating panels	Fumed silica, metalized polymer	0.008	180-210	A2	∞	90-172.5	-	X	-	-	-

table 2.2 application of the different insulating product varieties

Material	Facades						Roofs					Floors			
	New constructions				Existing structures		New constructions			Existing structures		New constructions		Existing structures	
	Cavity wall	Wet render systems	Dry cladding systems	Timber frame construction	Cavity wall	Insulation on the Inside	Pitched roof	Flat roof	Prefab roof element	Pitched roof	Flat roof	Wooden floor	Concrete floor	Wooden floor	Concrete floor
Inorganic: fibrous															
Glass wool															
Flocks	X	-	-	X	X	-	-	-	-	X	-	-	-	X	-
Panels	X	X	X	X	-	X	X	X	X	X	X	X[1]	X	X[1]	X
Rolls	-	-	-	X	-	X	X	X[2]	X	X	X[2]	X[1]	X[1]	X[1]	X[1]
Rock wool															
Flocks	X	-	-	X	X	-	-	-	-	X	-	-	-	X	-
Panels	X	X	X	X	-	X	X	X	X	X	X	X[1]	X	X[1]	X
Rolls	-	-	-	X	-	X	X	X[2]	X	X	X[2]	X[1]	X[1]	X[1]	X[1]
Inorganic: cellular															
Calcium Silicate															
Panels	-	-	-	-	-	X	-	-	-	-	-	-	-	-	-
Foam glass															
Panels	X	X	X	-	-	X	-	X[3]	-	-	X[3]	-	X	-	X
Perlite															
Panels	-	-	-	-	-	-	-	X	-	-	X[3]	-	-	-	-
Granules	X	-	-	-	X	-	-	-	-	X	X[4]	-	X[5]	X[5]	X[5]
Vermiculite															
Panels	-	-	-	-	-	-	-	X	-	-	X	-	-	-	-
Granules	-	-	-	-	-	-	-	-	-	X	-	-	X[5]	X[5]	X[5]
Organic-petrochemical: cellular															
Expanded polystyrene (EPS)															
Panels	X	X	X	X	-	X	X	X	X	X	X[3]	X[1]	X	X[1]	X
Granules	X	-	-	X	X	-	-	-	-	X	-	-	-	-	-
Extruded polystyrene (XPS)															
Panels	X	X	X	-	-	X	X	X	-	X	X[3]	X[1]	X	X[1]	X
Phenol formaldehyde (PF)															
Panels	X	X	X	-	-	X	X	X	X	X	X[3]	X[1]	X	X[1]	X
Polyurethane (PUR)															
Panels	X	X	X	-	-	X	X	X	-	X	X[3]	X[1]	X	X[1]	X
Injectable foam	-	-	-	-	X	-	-	-	-	-	-	-	-	-	X
Polyisocyanurate (PIR)															
Panels	X	X	X	-	-	X	X	X	X	X	X[3]	X[1]	X	X[1]	X
Urea formaldehyde (UF)															
Injectable foam	-	-	-	-	X[6]	-	-	-	-	-	-	-	-	-	-
Organic – renewable: fibrous															
Cellulose															
Flocks	-	-	-	X	-	X	X	-	X	X	-	-	-	-	-
Panels	X[7]	-	-	X	-	X	X	X[2]	X	X	-	-	-	-	-
Coconut															
Panels	X	-	-	-	-	-	-	-	-	-	-	X	-	X	-
Flax (flax wool)															
Flocks	-	-	-	X	-	X	X	-	-	X	-	-	-	-	-
Panels	X	-	-	X	-	X	X	X[2]	X	X	X2	X	-	X	-
Rolls	-	-	-	X	-	X	X	X[2]	X	X	X2	X	-	X	-
Hemp (hemp wool)															
Flocks	-	-	-	X	-	X	X	-	X	X	-	X	-	X	-
Panels	X[7]	X	X	X	-	X	X	X	X	X	X	X	X	X[1]	X
Rolls	-	-	-	X	-	X	X	X[2]	X	X	X[2]	X	-	X[1]	-
Recycled cotton															
Flocks	-	-	-	-	-	-	-	-	X	-	-	X	-	X	-
Panels	X[7]	-	X	X	-	X	X	X[2]	X	X	X[2]	-	-	-	-
Rolls	X[7]	-	-	X	-	X	X	X[2]	X	X	X[2]	-	-	-	-
Sheep wool															
Panels	X	-	-	X	-	X	X	X[2]	X	X	X[2]	X[1]	X[1]	X[1]	X[1]
Rolls	X	-	-	X	-	X	X	X[2]	X	X	X[2]	X[1]	X[1]	X[1]	X[1]
Wood wool															
Panels	X	X	X	X	-	X	X	X	X	X	X	X[1]	X	X	X[1]
Organic – renewable: cellular															
Expanded cork															
Panels	X	X	X	-	-	X	X	X	-	X	X	X	X	X	X
Granules	X	-	-	-	X	-	X	-	-	X	-	-	-	-	-
New technology materials: foil															
Thermosheets	-	-	-	-	-	X	X	-	-	X	-	X	X	X	X
Thermos cushions	-	-	-	-	-	-	X	-	-	X	-	X	X	X	X
New technology materials: cellular															
Aerogel															
Rolls	X	X	X	X	-	X	X	X[2]	X	X	X	X	X	X	X
Granules	X	-	-	X	X	X	-	-	-	-	-	-	-	-	-
Expanded polylactic acid															
Panels	X	X	X	X	-	X	X	X	X	X	X	X[1]	X	X	X
Granules	X	-	-	X	X	X	-	-	-	-	-	-	-	-	-
Vacuum panels	X	X	X	X	-	X	X	X	X	X	X	X	X	X	X

---

[1] Insulation must be fitted underneath the floor

[2] Insulation must be fitted on the inside of the roof

[3] Insulation must be fitted on the outside of the roof

[4] In combination with bitumen

[5] Can be used as addition to mortars or as levelling granules

[6] Only used to restore existing cavity walls filled with UF-Foam

[7] Possible if protected against water (foil, material coating, or air cavity between insulating material and outer wall)

2.2 Selection of materials

To limit the number of materials for which the LCA data will be collected, a selection will be made. This selection will be based on four properties:

1. Price
2. Thermal conductivity / thickness
3. Resource availability
4. Practical application

Two of these properties are already mentioned in table 2.1, namely price and thickness. By combining these two properties into a graph, a first selection can already be made. In figure 2.2.1 the price and thickness of the materials suitable for application in a cavity wall are displayed.

From the graph it is clear that a number of materials have a low thermal conductivity and thus perform well on thickness (e.g. vacuum insulation panels and aerogel). However, the price of these materials is high. This high price will be a barrier in the use of these materials. Large scale usage of these materials is therefore not expected on the short term. Other materials have a bad performance on both thickness and price, and for that reason will not be used for insulation in large quantities as well. These materials are coconut and perlite. Foam glass, wood wool and cork do not perform well on both price and thickness and are therefore not taken into account for the LCA assessment.

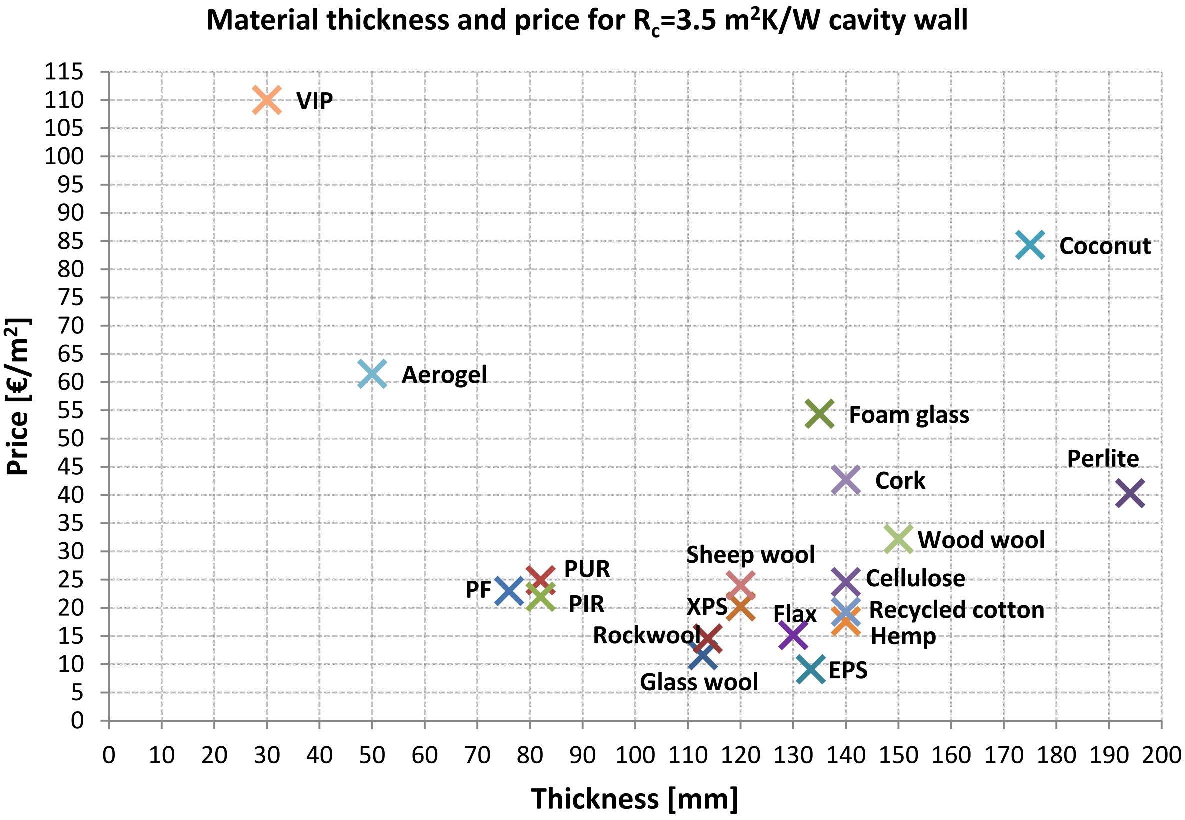

figure 2.2.1 price and thickness of materials in order to reach R_c=3.5 m^2·K/W

Resource availability and practical application

When looking from a resource availability point of view, sheep are not an option to deliver large quantities of insulating material. In the most favourable situation, a sheep delivers 4 kg of wool per year (Hasselaar, 2004). Calculating with the lowest sheep wool density of 25 kg/m^3 results in 6.25 sheep per m^3 of insulating material. The number of sheep needed to fill the empty cavity wall volume estimated in section 3.3, would be 62.5 million. As a comparison: the amount of sheep in the Netherlands in 2010 was 1.13 million (Statistics Netherland, 2011c). A similar calculation can be done for recycled cotton. In 2010, the amount of collected textile was 67 million kg (Statistics Netherlands, 2011c). This divided by the density of recycled cotton insulation gives 3.7 million m^3 of insulating material. However, not all the collected textile is cotton, which would mean that the total amount of insulating material that can be produced from recycled textile is even lower. Both sheep wool and recycled cotton are not suitable for mass production of insulating and are thus not taken into account for the LCA assessment.

Cellulose insulation is made from recycled paper. The amount of recycled paper in the Netherlands alone was 1076 million kg in 2010 (Statistics Netherlands, 2011d). In theory, the resource availability for cellulose insulation is good. Since cellulose insulation is hard to use in a cavity wall (needs good support and rain shelter) it is not taken into account.

XPS is a material that is often used for perimeter (area of a wall or foundation that is partly underground) insulation and not so much for the insulation of cavity walls. Since the price for XPS is only just below that of PUR, PIR or PF foam products, it is not likely to be used within cavity walls and is therefore not taken into account.

The remaining insulating products (glass wool, rock wool, EPS, Flax, Hemp, PF-foam, PUR, PIR) will be assessed. Especially mineral wool and EPS need to be addressed, in view of the fact that these materials represent almost the entire European insulation market. Mineral wools have a European market share of 60%. EPS and other petrochemical derived foams form 27% of the European market. The remaining materials have a total market share of 13% (Pappadopoulus, 2005). In the Netherlands, this 13% is more likely to be 1-2%, since the Dutch insulation market is dominated by mineral wools and petrochemical foam products (Lustig and Verlind, 2011). The hard foam products PIR, PUR and PF foam are taken into account because of the low thermal conductivity and the relatively low costs of the materials. For renovations where less space is available for insulation, these materials could provide a solution. Hemp and flax are taken into account because these renewable materials can be used in a cavity wall against a reasonable price.

2.3 Functional Unit and impacts of interest

For the assessment of the LCA studies, a functional unit has to be defined. In section 2.1, a cavity wall construction is used to determine the thickness and thus the price of insulating materials. For the LCA assessment, the cavity wall construction is again decisive for the amount of insulating material needed. The chosen functional unit for the assessment is the insulating material needed for the insulation of 1m^2 cavity wall surface to an R_c-value of 3.5 m^2·K/W:

> *"The manufacture, use and disposal of insulation material for a 1 m^2 cavity wall surface of a Dutch domestic house to an R_c-value of 3.5 m^2·K/W for a lifetime of 50 years."*

According to VROM (2007, pp. 24), the cavity wall is the most common wall construction in the Netherlands. Approximately 78% of the existing housing stock is constructed with cavity walls (VROM, 2009). Furthermore, almost all newly built houses are constructed with cavity walls. The thermal resistance value of 3.5 m^2·K/W is taken from the coming building decree for 2012. This value is valid for newly constructed houses, renovations and building extensions. Renovation and building extensions can only take place with a permit of the local municipality. To obtain this permit, the requirements of the building decree have to be met, including the requirements for insulation. The lifetime of 50 years is chosen because this is the design lifetime of houses, after which a renovation or refurbishment is often needed (Vellekoop, 2011). After this lifetime, the house is either renovated or demolished. In the case of demolishment, the end-of-life options of the insulating materials need to be investigated. Because of the different sources from which the materials originate (e.g. petrochemical, organic, or inorganic), the end-of-life options may differ per material. Therefore the disposal of the insulating materials is also taken into account next to the manufacture and use of the materials.

2.4 Sources and assessment

Because full LCAs of insulation materials are already conducted by different institutes and companies, it is not useful to perform an own cradle-to-grave LCA once more. Therefore, multiple LCA studies are used to create an assessment of the environmental and health impacts of the selected insulating materials.

Multiple databases and sources are used, because no single source contains LCA data for all the selected materials. Furthermore, it is interesting to see if, and how large variations between the different sources and databases are. Beside LCA data, also health aspects of insulating materials are looked into. Health aspects are usually not part of an LCA, meaning that for information on health aspects, a variety of sources need to be consulted. The databases and reference works listed below are used to assess the different insulation materials:

- **Environmental product declarations**

Producers and branch organisations provide environmental product declarations (EPDs) for their products. The German institute for Bauen und Umwelt (IBU) has devised a format for these EPDs (IBU, 2009a). Via the institute, the EPDs can be obtained. The EPDs contain information on the production, use and waste phase of the products and the emissions and energy use thereof. The EPDs also provide information about the end-of-life options of the materials and health issues.

- **NIBE reference works**

The Dutch institute for construction biology and ecology (NIBE) has created reference works of building materials. In these reference works, the building materials are sorted per application. Cavity wall insulation for instance has its own paragraph in the reference work. In the reference works, the materials for a certain application are categorised in ‘Environmental classes’, ranging from 1a (b,c) to 7c, in which 1a represents the lowest environmental impact. The reference works are very extensive. Not the usual three, but five life phases are indicated for the construction materials: raw materials phase, production phase, construction phase, use phase, demolish/waste phase. This leads to very extensive environmental indicators as well. Next to emissions, also nuisance (light, sound, stench, risk of calamities) and depletion (biotic, a-biotic, energy carriers, land use) are considered. By expressing all of these values in shadow prices, the environmental index is calculated for the product. Information on health issues is also provided for the materials (Haas, 2008).

- **Ökobau.dat[8]**

This is a German database created by PE international for the German ministry of Traffic, Construction and Urban development and contains 650 processes, all of which are related to building materials. Since the database is created in 2009, most of the processes are up to date. In the database information can be found on energy use and emissions during production. The majority of the processes are cradle-to-gate, but the database also contains end-of-life processes to obtain a cradle-to-grave analysis.

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[8] The Ökobau database is a publically available database. It can be found at: http://www.nachhaltigesbauen.de/baustoff-und-gebaeudedaten/oekobaudat.html

- **Producer specific information**

Some producers provided product specific information for their products. This could be LCAs, but also specific information on the waste phase of the product, or certain components in the products. This is valuable information, since it is the most up to date and product specific.

- **Ecoinvent (SimaPro)**

Another LCA database in which insulating materials can be found is Ecoinvent. However, the Ecoinvent database does net specialize on building materials. This means that some of the data might be out-dated or not usable because the Ecoinvent database often uses Swiss production standards.

- **(Academic) literature**

Where needed, literature is used to find additional or missing information.

The overview of table 2.3 shows the data source used per material and analysis type. Product specific information was provided by Isover and the association of EPS producers (EUMEPS) in the form of EPDs.

table 2.3 data sources per material and analysis type (X=data available, - = no data)

	Cradle-to-gate			Cradle-to-grave			
Material	**Ecoinvent**	**Ökobau**	**EPDs**	**Ökobau**	**EPDs**	**NIBE**	**Literature**
Glass wool	X	X	X	-	X	X	-
Rock wool	X	X	X	-	X	X	X
Gray EPS	-	-	X	-	X	-	-
White EPS	X	X	X	-	X	X	-
Flax	-	X	-	X	-	X	X
Hemp	-	X	-	X	-	-	-
PUR/PIR	-	X	X	-	X	X	-
PF-foam	-	-	-	-	-	X	-

The databases and sources listed above will be consulted to assess the materials on the environmental impacts categories listed below. Considering that these are the impact categories for which almost all of the data sources provide data, a comparison is possible.

- Cumulative energy demand (MJ)
- Green house gas emissions (kg CO_2 eq, GWP 100)
- Acidification (kg SO_2 eq)
- Eutrophication (kg PO_4 eq)
- Ozone depletion (kg CFC-11 eq)

Health aspects can be product specific (e.g. fibres in mineral wool products), it is thus not possible to define a standard for these aspects. Therefore the health aspects will be discussed separately from the environmental impacts.

2.5 Input parameters

In table 2.1 a number of properties are given for insulating materials. For some materials in table 2.1 larges differences can be seen between for instance density and thermal conductivity. Rock wool for example is produced with many different densities, ranging from 25 – 200kg and its thermal conductivity ranges from 0.030 to 0.040 W/m·K (IBU, 2008). The density and thus the thermal conductivity of an insulating material depends on its application. For flat roofs insulated on the outside, a different density is needed than for the insulation of pitched roofs or cavity walls. Since the functional unit is the insulation of a cavity wall, the corresponding properties of insulating materials suitable for cavity walls are used.

The properties of the insulating materials suitable for application within a cavity wall and the resulting mass of the functional unit are listed in table 2.4. These are the properties used to establish the functional unit. As can been seen in the table, rock wool cavity wall products have a wide density range. A higher density results in a somewhat lower thermal conductivity. For the assessment, an extra separation is made. EPS is split in two types of EPS, namely 'white EPS' and 'Gray EPS'. The reason for this separation is because of the enhanced properties of gray EPS. Gray EPS contains graphite, which acts as a radiation absorber. As a result of this absorption, the thermal conductivity for gray EPS is lower than that of white EPS. The calculated thicknesses of the functional units are converted into the trade thicknesses of the products (equal to the price calculation method of appendix B).

table 2.4 input parameters of insulating materials

Material	Density [kg/m^3]	Thermal conductivity [W/m·K]	Mass of functional unit [kg]
Glass wool	25 - 28	0.033 – 0.035	2.99 - 3.30
Rock wool	45 – 70	0.033 – 0.035	5.40 - 8.10
Gray EPS	15 – 16.6	0.032	1.65 – 1.83
White EPS	15 – 16.6	0.036 - 0.040	1.90 – 2.25
Flax	30-38	0.038 – 0.042	4.20 – 4.94
Hemp	38	0.040	5.32
PUR/PIR	30 – 33	0.024 – 0.028	2.46 – 3.05
PF-foam	35.6	0.021	2.71

2.6 Results

For the life cycle of insulating materials three life phases are defined and investigated:

1. Resource extraction and production phase
2. Use phase
3. Waste phase

After applying the materials to the functional unit (the cavity wall is insulated), no more energy or materials are used. Consequently, the use phase is negligible. In order to assess the different sources and materials, the data from the LCA sources listed above is converted to the functional unit. In figure 2.6.1, the cumulative energy demand (CED) of the different insulating materials is given per functional unit for a cradle-to-gate analysis. The CED includes both renewable and non renewable energy use. Hemp and flax have the highest share of renewable energy (25-30%) in their CED. For the other materials, the share of renewable energy in the CED is less than 10%, with EPS, and PUR/PIR scoring the lowest values: between 1-3%. In the graph, the effect of the radiation absorber in gray EPS is visible. The use of graphite in EPS does not affect its density, but lowers the thermal conductivity, resulting in less material for the functional unit, and consequently a lower CED (EUMEPS, 2011).

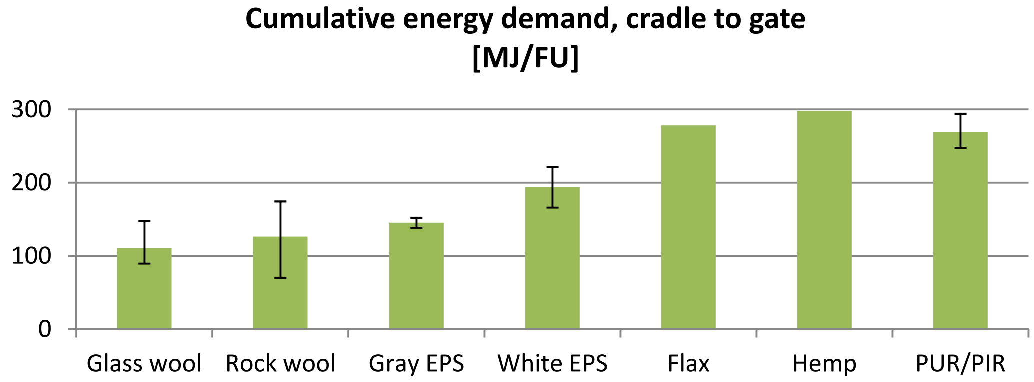

figure 2.6.1 cumulative energy demand for insulating materials, cradle-to-gate

Due to absence of data for PF-foam, no cradle-to-gate data is presented for PF-foam. From figure 2.6.1 it can be seen that the mineral wools use the least amount of energy per functional unit while flax, hemp and PUR/PIR use the most. In appendix B a description of the production processes of the different materials is given. Glass and rock wool are produced in a similar manner, which due to its bulk size and resources (recycled glass for glass wool, diabase and basalt for rock wool) results in the lowest cumulative energy demand. Next to that, the output products of the production process have a lower density than the input materials. For instance, for the production of rock wool, 1 m^3 of basalt is turned into approximately 90 m^3 of rock wool insulation (depending on the rock wool density).

Since the different LCA data sources provide different numbers, there is a spread in the calculated results. This spread is indicated with error bars in figure 2.6.1. The main bar indicates the average of the calculated results. For rock wool a large spread is found. This spread is a result of two factors. One factor is the density of the material. For cavity walls, multiple products are available with a density varying from 45 to 70 kg/m^3. Both densities are taken into account here, causing part of the spread. The second factor is the difference in LCA values. An EPD for rock wool presents a CED of 13 MJ/kg rock wool, whereas Kellenberger present approximately 22 MJ/kg rock wool (IBU, 2008; Kellenberger, 2007). This difference in values can be explained by the fact that IBU and Kellenberger assume different production facilities in their analysis. Kellenberger uses a Swiss plant, whereas IBU uses data from German plants.

Another explanation is the age of the data. The data provided by Kellenberger stems from 2002, while the data in the IBU EPD is said not to be older than five years.
Flax, hemp and PUR/PIR materials have the largest CED. For flax and hemp, the CED was only derived from the Ökobau database, since Ökobau is the only database containing cradle-to-gate LCA data for these materials. According to the EPD for PUR/PIR by the IBU, the high CED for PUR/PIR finds its origin in the raw materials: only 1% of the CED is related to the production process (IBU, 2010).

Cumulative energy demand: cradle-to-grave
When taking into account the waste phase of the insulating materials, the graph changes in favour of EPS. In figure 2.6.2 the CED for the total life cycle of the products is depicted. In all of the LCA data sources, incineration is chosen as the end-of-life solution for EPS and the recovered energy from incineration is deducted from the other life phases. Due to the heating content of EPS, the cradle-to-grave CED is lower than the cradle-to-gate CED.

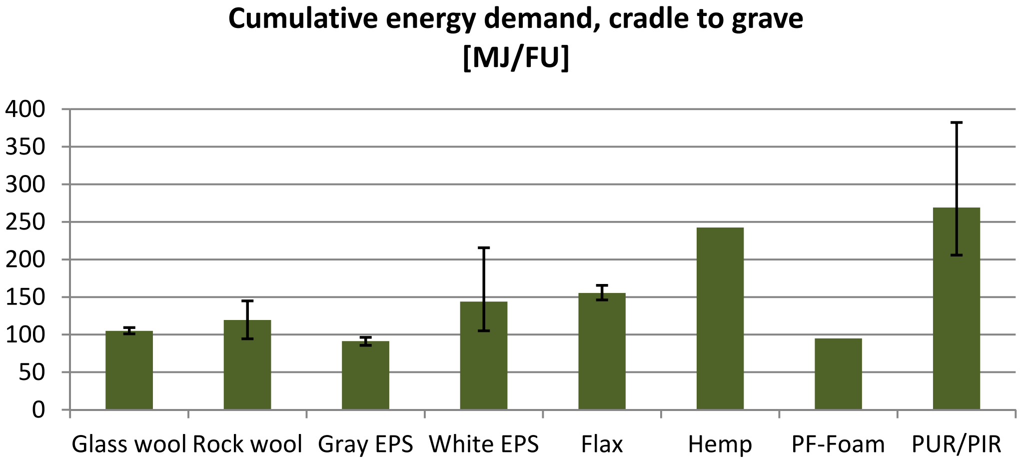

figure 2.6.2 cumulative energy demand for insulating materials, cradle-to-grave

In the case of rock and glass wool, the CED remains nearly the same. As an end-of-life solution, land filling is used in all but one of the data sources. Schmidt (2010, p.56) uses ‘road fill’ as a recycling option for rock wool. Since mineral wools are inorganic materials with a very low heating content, incineration of the products is not feasible. When incineration is used as the end-of-life solution, the efficiency of the waste incineration facilities used in the LCA analyses by for the IBU EPDs and Ökobau are between 60-65% (Spang, 2012). NIBE assumes a thermal efficiency of 20% and an electrical efficiency of 7% for waste incineration facilities (NIBE, 2012a). For all the materials, the entire calorific value of the functional unit is deducted.

Flax and hemp based insulating materials perform better from a CED point of view when the full life cycle is taken into account. This is primarily because of the energy recovery during the waste phase which again is incineration. For hemp, the data availability is poor. In order to simulate the full life cycle, the Ökobau database advises to use an incineration process for chipboard (“EOL Holzwerkstoffe in Müllverbrennungsanlage”). By combing this end-of-life process and the process for hemp production, a cradle-to-grave analysis was modelled.

For flax, cradle-to-grave analyses are performed by both NIBE and Schmidt. Schmidt assumes ‘road fill’ as the waste scenario for flax, where NIBE uses incineration as the waste scenario. Despite of the difference in waste scenario, the calculated values for the functional unit do not differ much (166 MJ/FU

for Schmidt and 146 MJ/FU for NIBE). Equal to hemp, the Ökobau data for flax are combined with the advised incineration scenario mentioned above. This results in a CED of 154 MJ/FU, so the same order of magnitude as NIBE and Schmidt.
Similar to hemp, LCA data for PF-foam is almost unavailable. Only NIBE can provide a full cradle-to-grave analysis for the use of the material in a cavity wall. Also for PF-foam, the waste scenario is incineration with deduction of energy recovery. Due to the low thermal conductivity of PF-foam, a product of only 76mm thick is required, resulting in a low CED.

The material with the highest average CED and the largest spread is PUR/PIR. The LCA data used is provided by an EPD created by both the IBU and the branch organisation for PUR/PIR producers and a cradle-to-grave analysis by NIBE. Between the calculated results for the functional unit a difference of a factor two is found. This difference occurs because of the fact that the PUR/PIR branch organisation has been calculating with the newest and most favourable figures, where NIBE used older data (NIBE, 2012b). Another factor that plays a role is the fact that when NIBE encounters an uncertainty within its analysis, it always chooses the worst case scenario (Haas, 2008), where PUR/PIR producers are likely to choose the most favourable scenario. Both the waste scenarios are the same: incineration with a deduction of the recovered energy. As mentioned above, NIBE uses a lower efficiency for the waste incineration facilities, which also cause a part of the spread. A similar situation is encountered for EPS, where the large spread is solely because of the high values provided by NIBE.

Greenhouse gas emissions

In the graph of figure 2.6.3 the greenhouse gas emissions (GHG-emissions) of the insulation materials are given for both the cradle-to-gate (left column) as the cradle-to-grave (right column) analysis. A large spread in values is found for rock wool, but this is because of the variation in density between the rock wool cavity wall products. Between the GHG-emissions of glass and rock wool a difference is observed. Although in figure 2.6.2 the CED for glass and rock wool are almost equal, the difference in production process causes a disparity for the GHG-emissions of the wools. Glass wool is produced with the use of natural gas (occasionally electricity), whereas rock wool is produced in a cupola oven fed with cokes. The difference in emission factor between the fuels could be the cause for the difference in GHG- emissions. For EPS, flax and hemp the increase in GHG-emissions in the waste phase is as a result of the chosen waste scenario (incineration) and the fact that the CO_2 uptake during the growth of the plants is taken into account in the cradle-to-gate analyses (deducted). For PF-foam NIBE (2008, pp. 128) assumes 90% incineration, but since there is no cradle-to-gate analysis available, a comparison is not possible. PUR/PIR materials have the highest GHG-emissions, which according to the IBU (2010, pp. 14) can be allocated for over 95% to the raw materials needed for the production (MDI and polyol). A way of reducing the GHG-emissions would be to recycle the PUR/PIR products. This is further discussed in section 2.7.

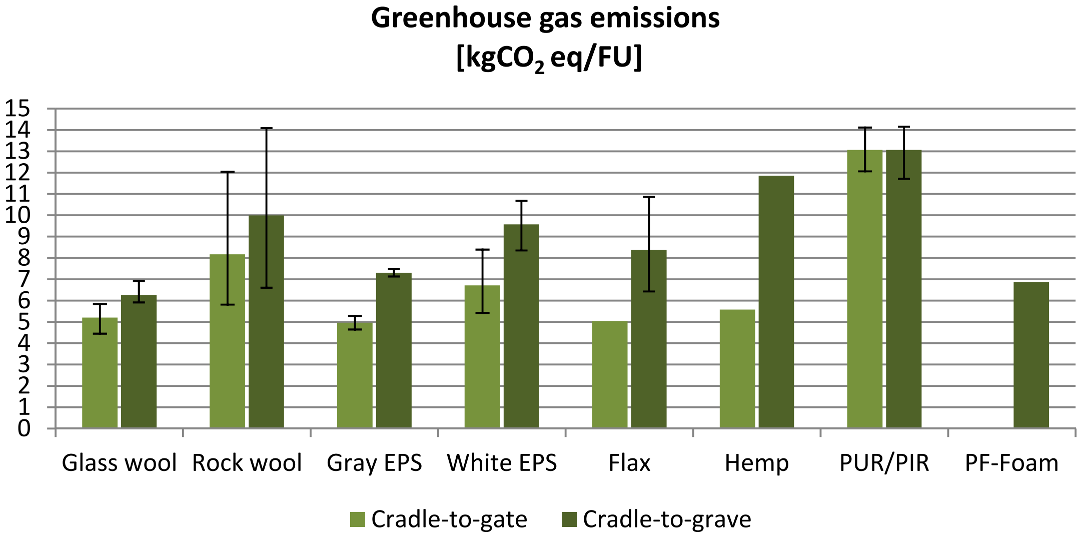

figure 2.6.3 global warming potential of insulating materials

Eutrophication

Similar to the GWP, the eutrophication potential (EP) of the insulating materials is presented graphically in figure 2.6.4. Again, both the cradle-to-gate as the cradle-to-grave analysis results are presented. The most prominent spread in results are found for PUR/PIR products in the cradle-to-grave analyses. For the PUR/PIR cradle-to-gate analysis, the values from an EPD are used. This EPD is created by the German association of PUR/PIR producers (IVPU) in collaboration with the IBU and should be representative for the entire branch (IBU, 2010). The EPD provides a cradle-to-gate as well as a cradle-to-grave analysis. For the cradle-to-grave analysis, the analysis by NIBE (Haas, 2008, pp. 126) was also considered. Values from both the IVPU and NIBE cradle-to-grave analysis are used, resulting in a discrepancy between the calculated results. For their analysis, IVPU has used three modern production facilities and combined the values from the three plants into one analysis. For their analysis, NIBE uses Simapro which is based on the ecoinvent database. In the analysis, the ecoinvent data is used after adapting the transport figures to the Dutch situation (NIBE, 2012b). As said before, NIBE assumes the worst case scenario in case of uncertainties in the analysis. Since the used EPD is relatively new (2010) it might be that process specific data was not yet available at the time of the NIBE analysis, causing more uncertainties and therefore higher estimations.

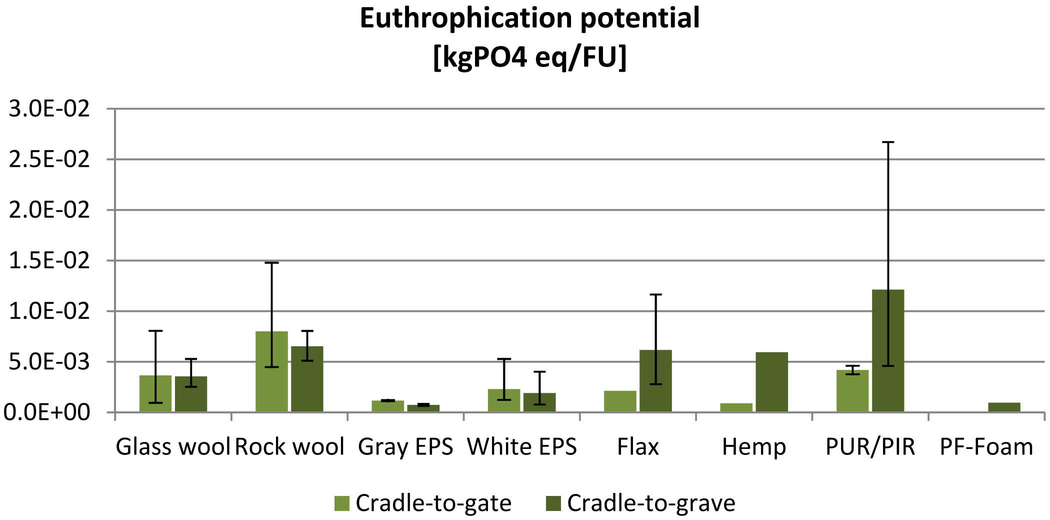

figure 2.6.4 eutrophication potential of insulating materials

A similar issue is found for the glass wool cradle-to-grave analysis. The highest value found for glass wool is coming from the ecoinvent database, which models a process out of the year 1991, with data dating back to 1993-1995, which is clearly outdated (Kellenberger et al, 2007). For rock wool the ecoinvent data is also relatively old (2001). In addition, the data from ecoinvent originates from a Swiss facility, whereas the data from the EPD comes from German facilities.

Apart from the age of the dataset, the spread for glass wool is also explained by the used production process and subsequently the fuel that is used for the process. Glass wool can be produced in an electric furnace (rare), but also in a natural gas fired furnace (common practice). Multiple LCA analyses are used based upon different production facilities in which both processes are used, resulting in large difference in values for glass wool. According to Kellenberger et al (2007, pp. 427) and the EPD for Knauf glass wool (IBU, 2011) natural gas only accounts for 40% of the production energy, the rest is electricity. The chosen electricity mix is thus of great influence on the environmental impacts.

Acidification
In figure 2.6.5 the results for acidification are presented. For acidification the spread between the results are large for glass wool, rock wool, EPS and flax. For rock wool, the spread is again caused by the variation in density. The reason for the high acidification potential of rock wool is the use of cokes during the production. The results for flax deviate because of the difference in waste scenario. NIBE assumes 95% incineration (Haas, 2008, pp. 134) where Schmidt (2004, pp. 55) assumes road fill as the waste scenario. For glass wool the difference in values originates from the differences in values found in the EPDs from Schwenk (IBU, 2011a), Knauf (IBU, 2011b) and Isover (Isover, 2011) and the values from NIBE. However, for glass wool this time it are the producers (Knauf and Isover) that provide higher values than the Ökobau database, the NIBE reference works and the ecoinvent database. According to Isover, the data provided by the producers themselves is the most correct and up to date data. An explanation for the difference between the producers and the databases is again the used energy mix (gas or electricity) and the age of the data (van Rooy, 2011; Medard, 2012).

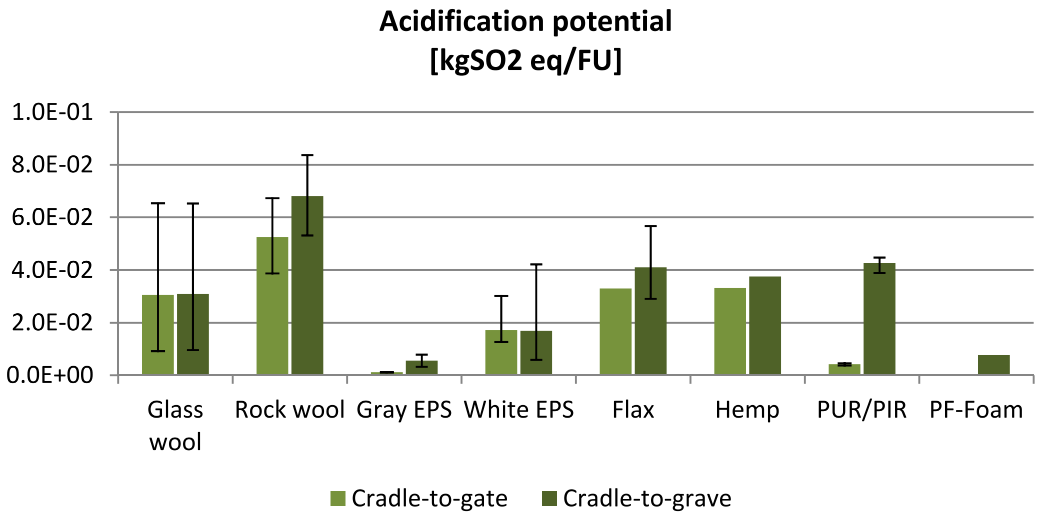

figure 2.6.5 acidification potential of insulating materials

The reason for the difference in values for white EPS is because of the antiqued database used by NIBE, which results in high values. At this moment, the EPS producers and NIBE are discussing the options of combining their knowledge into a new dataset for EPS. For now, the values provided by the EUMEPS EPD and the IBU EPS EPD (the values at the lower end in figure 2.6.5, are the most realistic (Lamers, 2011).

Ozone depletion potential

In figure 2.6.6 the ozone depletion potential (ODP) of the insulating materials is depicted. In order to be able to display the results properly, the results based on the values from the NIBE reference works for PUR/PIR and white EPS products are left out of the graph. According to NIBE (Haas, 2008, pp. 126) the ODP for PUR/PIR products is $1.14\cdot10^{-5}$kg CFC-11 eq. This value is much higher than the ODP values per kg product provided by IVPU (2010, pp. 3) that range between 2.8·10-8 and 6.6·10-8 kg CFC-11 eq. Since no PUR/PIR producer participated in the research, it is hard find a solid explanation for this difference. A possibility could again be the age of the dataset used by NIBE, as was indicated to be the problem for glass wool as opposed to EPS. For the case of EPS, NIBE (Haas, 2008, pp. 124) provides an ODP of $8.7\cdot10^{-7}$ kgCFC-11 eq, where both the IBU (2009, pp. 3) and EUMEPS (2011, pp. 2) present values in the range of $1.7\cdot10^{-9}$ and $5.1\cdot10^{-10}$ kgCFC-11 eq.

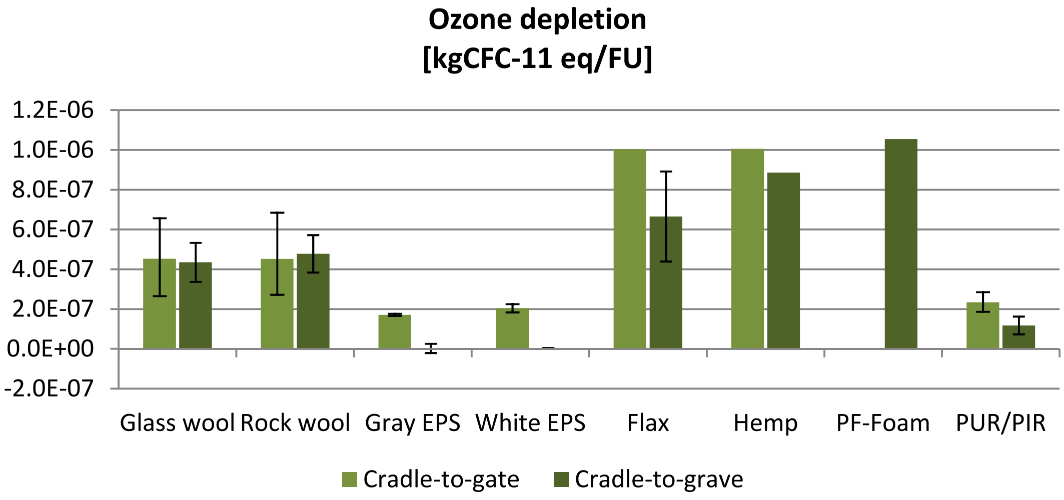

figure 2.6.6 Ozone depletion potential of insulating products

Due to credits from the incineration process, the insulating materials for which incineration was used as the waste phase solution, have a lower ODP in the cradle-to-grave analysis than the cradle-to-gate analysis. For gray EPS a negative value is obtained for the waste phase, due to the lower thermal conductivity of gray EPS compared to white EPS.

2.7 Alternative recycling options

In most the cradle-to-grave analyses found, incineration or land filling are the most common end-of-life solutions. In practice however, land filling and incineration do not need to be the solution of choice. For many materials, alternative solutions are already possible or under development.

Glass and rock wool

For glass and rock wool the chosen waste scenarios are either land filling or ‘recycling’ it as road fill materials. However, other waste options are also available for both rock and glass wool, particularly recycling the post-consumer material back into the production process. For both rock and glass wool this is already common practice. Especially in the case of rock wool, where used plant substrates made out of rock wool are returned to the production plant periodically. Contamination of the rock wool products is not a problem, since the temperatures inside the cupola oven will burn any organic contaminations and melt inorganic contaminations. For glass wool, very contaminated wool cannot directly be used and needs cleansing first. This is because the glass wool production is more sensitive to impurities (Schuurmans, 2011; van Rooy, 2011).

The majority of the CED used for mineral wools can be allocated to the production process (smelting of raw materials, spinning of fibres and curing the binder) (IBU, 2008). Recycling mineral wools will therefore not cause a large reduction of the CED. According to Schmidt (2004, pp. 59) the maximum reduction potential is 0.67 MJ/kg rock wool. For glass wool no such values are available, but because of the similarities between the production of glass and rock wool, a saving in the same order of magnitude is expected.

Another option already in use for both glass and rock wool is using mineral wool as a filler material in the production of bricks (IBU, 2008; IBU, 2011, van Rooy, 2011). Mineral wools are not only used for their thermal properties. Acoustic insulation of interior walls or other constructions can also be done with mineral wool. From used rock wool, other products than thermal insulation wool can be made. Rockwool (the company) for instance produces facade elements, which are made from the same materials as rock wool, only much denser and prepared against weather elements (Schuurmans, 2011).

EPS

In all of the LCA data sources, incineration is chosen as the end-of-life options for EPS. Incinerating EPS is however not the only solution. Another option for EPS is recycling EPS by shredding the EPS and adding it to the thermoforming process. Up to 20% shredded EPS can be added to virgin EPS pearls before thermoforming without any quality loss (the damaged EPS pearls do not insulate as well as the virgin pearls). Shredding EPS can be done 5-7 times, after which the product needs to be disposed (Lamers, 2011). Despite the fact that EPS can be recycled, this does not take place on a large scale yet. According to Lamers (2011) this is because of the low amount of used EPS returned to the production facility. EPS producers are keen on recycling EPS, but today’s supply of used EPS is too low to get even near the 20%. Analogous to PUR/PIR products, the raw materials are largely responsible for the CED. By using recycled EPS, this energy demand can be reduced, as is shown with two new processes in the ecoinvent database by Hischier (2010, pp. 25). The CED for EPS made out of 45% recycled EPS is 40% less than the CED for virgin EPS. When 100% recycled EPS is used, a CED reduction of 87% is achieved, compared to the CED for virgin EPS, also from the ecoinvent database (Kellenberger et al, 2007). A similar reduction is also found for the other environmental impacts. During the recycling, no distinction has to be made between gray and white EPS from a production point of view. Gray EPS pearls are already mixed with white EPS pearls for esthetical reasons (Lamers, 2011).

Flax and hemp
The end-of-life options for hemp and flax are similar, so the materials can be discussed together. In the found LCA datasets for hemp and flax, the materials are incinerated at the end of their lifetime. Another option that comes to mind when dealing with materials from renewable sources is composting. Composting of these materials is however not possible. This is because both flax and hemp are produced with (polyester) support fibres (around 15%, see appendix B) which are melted around the natural fibres. Separating the polyester from the natural fibres is therefore difficult. It is also possible to produce the support fibres out if renewable materials. A study done by the University of Stuttgart and PE-International has resulted in a polylactic acid (PLA) support fibre instead of polyester. Using PLA instead of polyester decreases both the CED as well as the GHG-emissions (Deimling and Bos, 2008). Next to that, replacing the polyester fibres by PLA fibres allows the hemp insulation products to be composted (Holzhey, 2011).

PF-foam and PUR/PIR insulation
Also for PF-foam and PUR/PIR insulation the chosen end-of-life option is incineration. For PUR/PIR insulation there is a recycling option: glycolysis. By the use of glycolysis, the polyurethane bonds are broken, converting PUR into one of its raw materials: polyol (Molero et al, 2006). The process of glycolysis is under development and has not been applied on a large scale yet. It is thus not yet possible to indicate if, and to what extent this process will contribute to decreasing the CED and environmental impacts of PUR/PIR products. The same goes for PF-foam, for which chemical separation processes are also under development. Especially for PF-foam such a separation process is welcome, because PF-foam only chars in incineration facilities (van der Woude, 2011).

2.8 Health aspects

Thermal insulating materials are used to insulate houses and building. Since people reside within these buildings, the health impacts during the use phase of the products must be known. Also the hazards of working with the insulating materials in times of constructing the building are important, because of the direct contact that construction workers have with the materials.

Glass and rock wool
Mineral wool consists of vitreous fibres which are bonded together with a binder. Health aspects concerning mineral wool arise from both the fibres and the binder. As can be read in appendix B, formaldehyde is a commonly used as a compound of mineral wool binders (phenol-urea-formaldehyde). These binders can emit formaldehyde which negatively impacts the indoor air quality. Formaldehyde can lead to irritation of the eyes and the respiratory system (Haas, 2008). In the building decree, a limitation of 120 µg/m^3 at an exposure of 30 minutes has been set to the amount of formaldehyde in indoor air (RIVM, 2007). Because of the formaldehyde emission, the RIVM (2007, pp. 75) mentions insulating materials as a possible contributor to the indoor formaldehyde concentration. This is mainly because of UF-foam, which is (almost) not used anymore in the Netherlands. Other materials such as chipboard, medium density fibreboard (MDF) and textiles (curtains, carpets) are also responsible for the indoor concentration of formaldehyde. Knauf, a large producer of glass wool has developed a new bio-based binder that does not contain formaldehyde. All of the glass wool produced by Knauf is produced with a formaldehyde-free binder. The binder can also be used in the production of rock wool. Unfortunately, Knauf was not willing to disclose the composition or raw materials used for this binder (Lustig and Verlind, 2011). Until now, Knauf is the only producer working with a bio-based binder. Both Isover and Rockwool however expect that in the near future, also their products will make use of a formaldehyde- free binder.

The fibres used for glass and rock wool are different in size. Glass wool fibres have a diameter between 2-9 µm, whereas the diameter of rock wool fibres ranges from 3-6 µm. Mineral wool fibres can cause health issues in two ways: skin contact and fibre inhalation. According to the RIVM (2007, pp. 153) skin contact with the fibres can cause irritation because the fibres pierce the skin. This phenomenon is worse for glass wool, since glass fibres are sharper than rock wool fibres. When fibres with a diameter smaller than 4-5µm are inhaled there is a chance on lung fibrosis (RIVM, 2007). Mineral wool fibres are not considered carcinogenic (RIVM, 2007; Lipworth et al, 2009). During the production and the construction phase the fibre concentration is the highest. For the construction phase the RIVM (2007, pp. 153) advises to cut the mineral wool products outside, so that no fibres end up indoors. After the products are installed, no more fibres are released. During the installation of mineral wool, it is advised to cover unprotected skin, wear goggles (when working overhead) and to make use of dust caps when working in unventilated spaces (IBU, 2011b).

EPS

In EPS insulating materials, hexabromocyclododecane (HBCD) is used as a fire retardant. The fraction of HBCD used in EPS is 0.5 to 1% of the total product. HBCD is physically bound in the material which limits the amount of HBCD off-gassing to 0.001% (Lustig and Verlind, 2011). So only a very little amount of HBCD is released by EPS. However, HBCD is lipophilic, causing bioaccumulation in fat tissue. Humans can come into contact with HBCD via inhalation and skin contact. HBCD can disrupt the human hormonal balance and may act as a neurotoxin (RIVM, 2007). Because of these properties, the European Chemicals Agency (ECHA) has placed HBCD on the ‘Substances of Very High Concern’ concern list within the REACH framework (ECHA, 2012). HCBD has also been placed on the ‘Substitute it now!’ (SIN) list (ChemSec, 2012). Replacement products are currently under development, but do not yet provide the same flame retarding properties as HBCD (Lustig and Verlind, 2011; Meuwissen, 2011).

Flax and hemp

For flax and hemp no significant health issues were found. A study by Koivula et al (2005, pp. 812-813) shows that both volatile organic compound (VOC) emissions and emissions of bacteria are negligible. The study also shows that emissions of moulds can be present at a high relative humidity (90%). Although the flax and hemp products are treated with ammonium phosphate or borax to protect them against fire and organism, correct placement of the materials is of great importance. If the materials get wet and are unable to dry, the growth of organism is inevitable.

PF-foam

According to the NIBE reference works (Haas, 2008, pp. 128) the use of PF-foam does not lead to any health issues. Only during the production of PF-foam health hazards could exist because of the use of phenol formaldehyde (Haas, 2008).

PUR/PIR insulation

During the production of PUR/PIR products, the toxic chemicals MDI and TDI are used. In-situ foaming of PUR foam therefore creates a risk of exposure to MDI and TDI (Haas, 2008). For panels, this risk is not present, since there is no proof for off-gassing of MDI and TDI at normal circumstances (IBU, 2010). When PUR/PIR products are heated, when the panels are cut or machined for instance, MDI and TDI can however be released (RIVM, 2007).

2.9 Discussion

Cumulative energy demand

The graphs from section 2.6 provide a clear image of the environmental impact and CED for both a cradle-to-gate as a cradle-to-grave assessment of the materials. In an analysis of the cradle-to-gate CED of insulating materials by Papadopoulos et al (2006, pp. 7), the same results were found as in figure 2.6.1. The cradle-to-gate CED is the lowest for glass wool, followed by rock wool and EPS. In the study by Papadopoulos, PUR/PIR has the highest CED. Flax and hemp were not assessed by Papadopoulos. According to Schmidt (2004, pp. 122) the reduction in heat loss by using insulating materials saves over 100 times the environmental impacts and energy associated with the production and disposal of the insulating products. In chapter 4, this will be investigated in more detail.

Density

An important remark that has to be made on the results from section 2.6, is that the results can only be used for cavity wall insulation products. This is because of the differences in density between cavity wall products and products for other applications. For example, if a flat roof is insulated on which it must be possible to walk, very different products and thus densities are needed. For example, rock wool suitable for the use on flat roofs has a density between 140-180kg/m^3, whereas EPS suitable for flat roofs has a density of approximately 25kg/m^3 (IBU, 2008; Lamers, 2011). These differences in density are dependent on the practical application and can be of influence on the CED and other environmental impacts. Another remark is that the results are there to provide insight in how the materials perform compared to each other and not to obtain exact values for CED or environmental impacts.

Another density related issue occurs for rock wool. For a cavity wall, the density of rock wool ranges from 45 to 70 kg with a thermal conductivity of 0.035 and 0.033 W/m·K respectively. Despite the lower thermal conductivity for the product with the highest density, the environmental impact of the products is higher. This means that the reduction in thickness of the insulating material does not lead to a reduction in environmental impacts. For every assessed impact category and CED, the heaviest product showed the highest impacts. However, the difference in thermal conductivity results in a thickness reduction of 5 cm. In practice, this reduction in insulation thickness means a slimmer cavity wall and therefore also a slimmer foundation. Whether this foundation reduction will result in a lower overall environmental impact for the building is questionable.

Flax and hemp

Surprisingly, the environmental impacts and CED for the bio-based material flax and hemp are relatively high compared to the other materials. For these high values two reasons are presented by Schmidt (2004, pp. 122-126) and Deimling and Bos (2008). The first reason is the use of fertilizer for plant growth. The energy requirement and the emissions of N_2O during the production of fertilizer contribute to the high environmental impacts and CED (Schmidt, 2004). The second reason is the use of polyester support fibres as a binder and the addition of flame retardants, which both require fossil fuels for their production. On top of that, the support fibres are melted before they are added to the hemp or flax fibres. The melting of the support fibres also requires fossil fuels as an energy source. When PLA is used instead of polyester, the CED becomes 14% lower, but is still relatively high (Schmidt, 2004; Deimling and Bos, 2008).

Practical limitations

For both renovations and new constructions, the choice of insulating materials depends on the type of application. Different applications ask for different materials. If for instance a wall is not completely flat, using stiff insulating panels can create pockets of air behind the panel, which has a negative effect on the thermal resistance of the wall. In such a case, flexible materials like mineral wools provide a solution. Their flexibility allows following the contours of the object to be insulated, thus eliminating air pockets behind the materials (van Rooy, 2011). For renovation projects, this is a useful property. On the other hand, the flexibility of mineral wools also makes them vulnerable. Especially for rock wool, compression of the material will damage the fibre structure with an increased thermal conductivity as a result. Also, mineral wools can sag out, resulting in a low thermal resistance. Mineral wool cavity wall products are engineered in such a way that this does not occur anymore these days provided that the products are mounted correctly (Schuurmans, 2011). Rigid foam products such as EPS are easy to use in automated processes like the production of roofing elements[9], because they can easily be trimmed or planed to size and glued (Lamers, 2011).

Data availability

Some of the results found in section 2.6 show large spreads. This is a result of the difference in values found in the assessed LCAs. Most of the high results are because of data that is either coming from ecoinvent or NIBE. Since NIBE uses the ecoinvent data for many of their analyses, their values are often high (NIBE, 2012b). In the case of PF-foam, company specific data is used by NIBE (van der Woude, 2011). Unfortunately, the LCA data by NIBE is the only data available for PF-foam insulation, so a comparison to other sources was not possible. Data availability is also a problem for hemp and flax wool. For hemp, the results are fully based on a cradle-to-gate process for hemp wool combined with an end-of-life process, both from the Ökobau database. For flax exactly the same procedure is used, but then with a flax wool cradle-to-gate process. The values for the flax cradle-to-grave analyses could be supplemented with data from both NIBE and literature, as can be seen in table 2.3.

The used EPDs from the IBU are created under supervision of the IBU, but often contain company or sector specific data. Although the IBU is an independent institute, it could be that the data used is somewhat optimistic, but more up to date than the ecoinvent data.

End-of-life scenarios

As discussed in 2.7, the used end-of-life scenarios in the LCA data sources are not always a reflection of what actually happens in practice. Some of the recycling alternatives discussed in section 2.7 are promising and need to be developed further. For EPS, the recycling of used EPS has a large reduction potential for both environmental impacts as the CED. Nonetheless there is a hurdle to overcome by the EPS producers: the fire retardant HBCD. Although developments are well on the way for finding a replacement for HBCD, recycling of EPS containing HBCD in the future could form a problem (Meuwissen, 2011; Lamers, 2011). In the coming years, the European Union will continue the REACH process for HBCD, which means that one day its use will be prohibited (Meuwissen, 2011). If this happens, it is not certain that the EPS produced in the past decades can be recycled (shredded) into new EPS that may not contain HBCD anymore. In future decisions the toxicity of HBCD must be assessed against the savings potential of using recycled EPS in the production process instead of virgin EPS.

Take back schemes could serve as important alternative to current end-of-life options. Although such schemes already exist for wastes and cut-offs from the construction site, it is necessary to also develop take back schemes for waste from demolishment.

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[9] See appendix A for an explanation on the use of roofing elements

Health aspects

Compared to other materials used inside homes (furniture, paints, textiles, chipboard and MDF), insulating materials are not responsible for a bad indoor quality (RIVM, 2007). Especially not when taken into account that insulating materials are never placed in sight, but always behind other materials. Materials used for the insulation of cavity walls are almost completely sealed off from contact with indoor air. In the case of renovation, insulation could be used on the inside of the walls. Here off-gassing or fibres could get in contact with the indoor air. However, if a house is renovated according to the Passive house criteria, the materials are completely covered in foils in order to get the building air tight. On top of that, the balance ventilation systems required for Passive houses will make sure that the concentration of impurities in the air will stay at a low level (Feist and Schienders, 2009). Because the discussed materials all have different types of health hazards, it is not possible to rank them accordingly.

3 Renovation potential

Of the 660 PJ needed for space heating, 325 PJ can be allocated to households, indicating that the space heating of households is responsible for 10% of the Dutch primary energy use (Menkveld and Beurskens, 2009). By renovating or replacing the thermal insulation in the existing building stock, the amount of energy needed for space heating can be reduced. Other options in the area of more efficient boilers and installations are of course also ways to decrease the energy use. However, the lifetime of many of such components is around 15 years, indicating that many of the installations have already been replaced by more efficient ones. For thermal insulation this is not the case, since it cannot break down or needs replacement. Especially when there is no insulation fitted during construction. As will be shown in section 3.2, insulation of the existing building stock has not been common practice, which results in large renovation potential.

3.1 Requirements for newly constructed houses

The main reason for the high energy demand for space heating is the poor insulation of the existing dwelling stock. Mandatory building insulation did not come in to force before the year 1975. Today, roofs, floors and walls of newly constructed houses are fitted with a layer of insulating materials of 80 – 100 mm thick when mineral wool or EPS is used in order to reach a thermal resistance (R_c)[10] of 3.5 $m^2 \cdot K/W$. Ever since the introduction of the building decree in 1992, the requirements for thermal insulation and the overall energy performance of buildings have been subjected to regulation. With the introduction of the Energy Performance Norm in 1995, it became mandatory to express the energy performance of a house into a number, the so called energy performance coefficient (EPC). For every new build house in the Netherlands an EPC-calculation has to be provided to obtain a building permit from the municipality. The calculation of the EPC-value must be done in accordance with the Dutch norm NEN 5128:2004. To ensure that the all calculations are done in the same way, a calculation tool has been devised, in which the required data for the calculation can be inserted. From this input, the EPC (a dimensionless number) is calculated with the use of equation 3.1.

$$\text{EPC} = \frac{Q_{\text{pres;total}}}{(330 \times A_{\text{g, living area}} + 65 \times A_{\text{g, loss}})} \times \frac{1}{\text{cEPC}}$$

equation 3.1 calculation of the energy performance coefficient (NEN 5128:2004).

In which:

$Q_{\text{pres,total}}$ = total annual primary energy (in MJ) used by building bound installations. This includes: heating of the house, domestic hot water, ventilation, pumps, fans, lighting and cooling installations (if present). The total primary energy can be reduced by adding solar panels or solar water heaters to the house.

$A_{\text{g,living area}}$ = living area of the house (ground floor surface plus storey surface) [m^2]

$A_{\text{g,loss}}$ = surface through which energy is lost (building envelope) [m^2].

cEPC = correction factor to align earlier version of the EPC calculation tool with the current version. At this moment, the cEPC is determined at 1.12. On the 1st of January 2012, norm NEN 5128:2004 will be replaced by a new norm (NEN 7120) in which the calculation method will be revisited.

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[10] In appendix B the calculation and meaning of the R_c-value are explained

At the introduction of the EPC in 1995, its value was 1.4 and has been lowered ever since. In 2011, the EPC has once again been lowered, this time to a value of 0.6. In 2015 the EPC should reach 0.4 (Agentschap NL, 2011). According to the European directive on energy performance of buildings, newly constructed houses should be “nearly zero-energy buildings” by the year 2020 (EC, 2010). An EPC-value of 0 would mean that a building is producing just as much energy as it is using. A building with an EPC of 0 can thus be considered a nearly zero-energy building. The development of the EPC-value over the years can be seen in figure 3.1.1. In the figure, the decline in natural gas usage (for space heating, tap water and cooking) over the years for terraced houses is also shown.

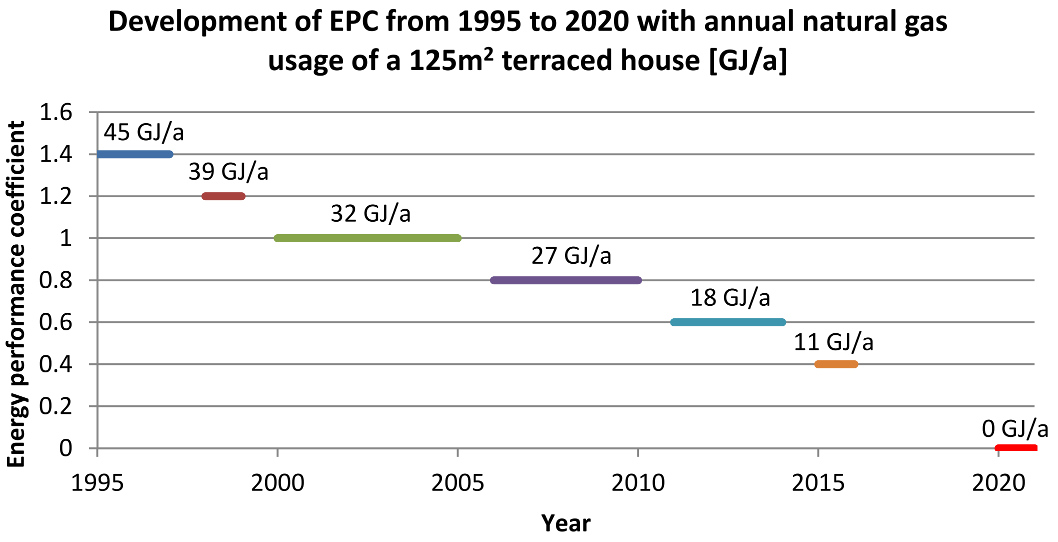

figure 3.1.1 development of the EPC since 1995 and annual gas usage of terraced house with 125m^2 floor surface [GJ/a] (Gerdes, 2010; Vreeman and ten Bolscher, 2009; Guerra Santin and Itard, 2010).

Vreeman and ten Bolscher (2009) have developed multiple concepts for reaching substantially lower EPC-values for the medium and longer term. In these concepts, also thermal resistance values are provided for the walls and roofs of the houses. These thermal resistance values are listed in table 3.1. The new thermal resistance requirement of 3.5 m^2·K/W of the 2012 building decree is too low to reach the current EPC-value of 0.6, especially for roof elements. When the EPC is lowered once more in 2015, the thermal resistance of the 2012 building decree is about half of what is needed to reach an EPC of 0.4. As can been seen in table 2.1, the R_c-value needed for an EPC of 0.4 is 6 m^2·K/W for walls, whereas the building decree prescribes 3.5 m^2·K/W. An EPC calculation is only required for new houses and not for renovations or building extensions. The building decree is valid for new houses as well as renovations and building extensions. The low EPC-values for new building result in measures that exceed the demands of the building decree. Therefore it is necessary that the building decree is revisited in time, so that also renovations and building extensions are insulated according the highest standards. The energy performance norm and the building decree should be adapted to each other, so that the mismatch between existing and new houses is limited.

table 3.1 EPC-values with corresponding R_c-values [m^2·K/W] (Vreeman and ten Bolscher, 2009)

	EPC = 0.8	EPC = 0.6	EPC = 0.4	EPC = 0
R_c wall	2.5	4	6	8
R_c roof	2.5	6	8	10

3.2 Estimation of renovation potential

In 2010, the number of houses in the Netherlands was 7.2 million compared to just over 1 million in 1899 (Statistics Netherlands, 2011b). During the past 110 years over 6 million houses have been built in the Netherlands. In figure 3.2.1 this development is plotted in a graph.

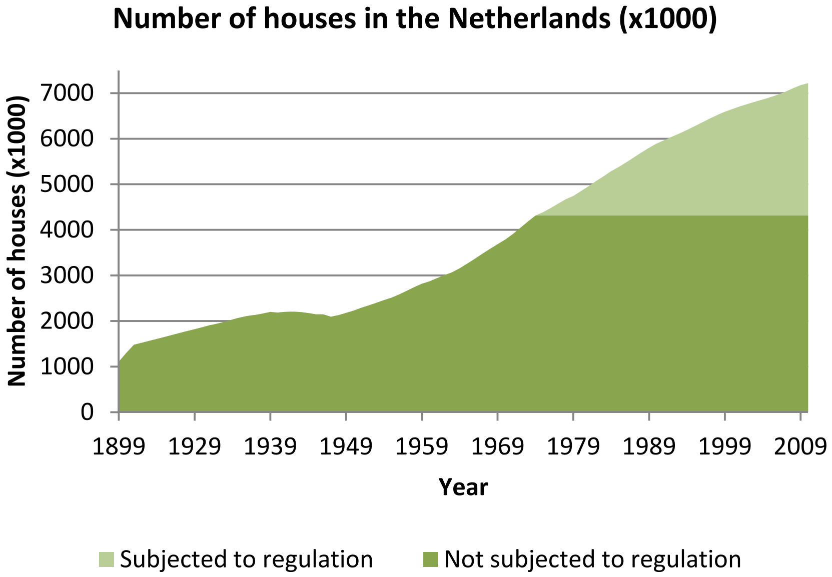

figure 3.2.1 development of the amount of houses in the Netherlands (Statistics Netherlands, 2011b)

Besides the development of the amount of houses in the Netherlands, figure 3.2.1 also shows the amount of houses that have not been subjected to any regulation regarding thermal insulation (the large dark area). From the graph it is clear that the major share of Dutch houses is built in time without regulation regarding thermal insulation. In figure 3.2.2, the share of buildings from different time periods in the 2009 housing stock (7.104.518 houses) is presented. According to Vellekoop (2011), houses are designed to have a lifetime of about 50 years (often used as the depreciation period by social housing corporations). This implies that the houses build in the period 1960-1970 are all at the end of their lifetime and in need of, or would benefit from a renovation. According to figure 3.2.2, this is 16% of the 2009 housing stock, which is equal to 1.13 million houses.

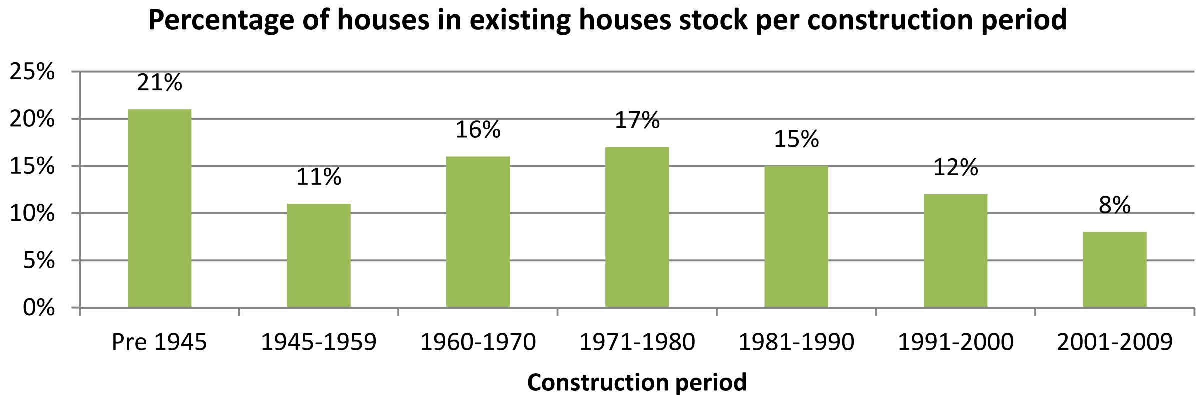

figure 3.2.2 share of houses from different period in housing stock (VROM, 2010)

In theory, the graphs from figure 3.2.1 and figure 3.2.2 could give an indication of the amount of houses that need to be renovated from an insulation point of view. However, with the introduction of the requirements for new buildings, the national insulation programme came into force, as is mentioned in the introduction. The goal of the national insulation programme was to insulate 2.5 million houses in 10 years time (800 thousand privately owned houses and 1.7 million rented houses), by offering subsidies for insulation. Although the programme was stopped prematurely, around 602,000 privately owned houses and over 1.2 million rented homes were granted a subsidy. In the period before the programme (from 1974 until 1978) already 420 thousand houses had been retrofitted with insulating material (Entrop and Brouwers, 2007). The fact that insulation of existing houses has already taken place, makes the graph from figure 3.2.1 unsuitable to estimate the amount of un-insulated houses.

A way of estimating the renovation potential of the existing housing stock is by combining two types of datasets. Both datasets are published by the Dutch government, albeit by different authorities. The first dataset used is from 2006. In 2006, the ministry of public housing, environmental planning and environmental management (VROM) has made an inventory of the so called 'Isolatiegraad' (or degree of insulation) of houses in the Netherlands. This was done by annual surveys of 5000 houses that are representative for the Dutch housing stock. The degree of insulation represents the percentage of houses in the total stock of which a certain element is at least insulated for more than 50%. Four elements are distinguished: the ground floor, closed facade, roof and glazing. When 50% of a facade, roof or ground floor surface is insulated, it is considered insulated. Glazing counts as insulated when 50% of the glass in a house is double glazing. Single glazed windows are considered not insulated (VROM, 2009). An important note here is that the degree of insulation does not say anything about the quality or thickness of the insulation itself. Since 1995, the degree of insulation has been monitored. The development in the degree of insulation until 2006 can be seen in figure 3.2.3.

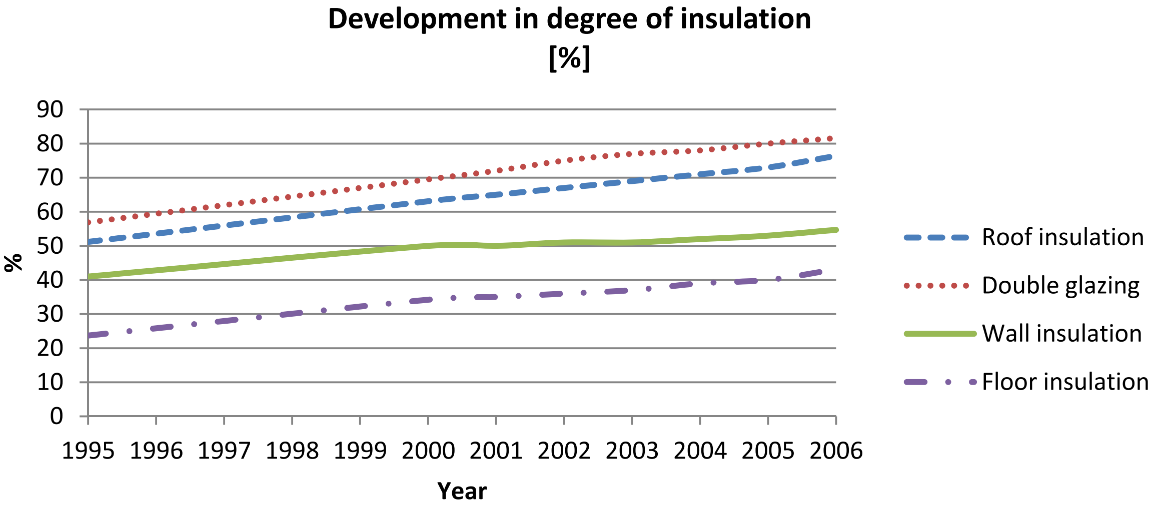

figure 3.2.3 development degree of insulation (Agentschapt NL, 2011; VROM, 2007)

Next to the degree of insulation, an inventory is also made of the type of façade constructions used for houses. It turns out that 78% of the Dutch closed façade elements is a cavity wall construction[11]. 15% of the houses has a solid brickwork construction. Construction types other than cavity wall or solid brickwork (e.g. prefab concrete or wood timber frame) form the remaining 7% (VROM, 2009). The

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[11] See appendix A for a description of common construction methods in the Netherlands

reason for the large share of cavity walls is historic. Houses were often built with materials that could be found nearby and on hand. This was the case for clay needed for brickwork. However, solid brickwork walls are not waterproof, causing water to leak through. To prevent this, the cavity wall construction was developed. According to Jeeninga and Volkers (2003, pp. 22) the cavity wall was used in 80% of the house built between 1930 and 1940 and in 95% of the building built in 1999. The fact that the majority of the closed façade elements were built as cavity walls and the low degree of insulation thereof, makes the cavity wall construction an interesting element in determining the renovation potential.

The second used dataset is published by SenterNovem. SenterNovem has developed so called reference houses to represent houses in the existing housing stock. These reference houses contain multiple versions of common types of houses built in a certain period in the Netherlands and their properties. For a standalone house for example, six types are defined: small and large standalone houses built pre 1966, in the period 1966-1988 and in the period 1989-2000. Other common types of houses are terraced-houses, 2 under 1 roof houses, maisonettes, gallery apartments and porch apartments. For all types of houses and their specific building periods, the closed facade surface is given, as is their volume (number of houses) in the 2006 building stock (SenterNovem, 2007a; Novem, 2001).

Combining the datasets

When the closed facade surface of the different types of houses and their volume in the existing building stock are multiplied and summed, an estimation of the total closed facade surface of houses in the Netherlands is obtained. This surface can be multiplied with the percentage of this surface that is cavity wall (the 78% mentioned above) which gives an estimate of the total cavity wall surface. According to VROM (2007, pp.31), the percentage of un-insulated cavity walls is 40%. Multiplication of the estimated total cavity wall surface by the percentage of un-insulated cavity wall, the total un-insulated cavity wall surface is obtained as presented by equation 3.2.

$$\sum(\text{Closed facade surface of reference house} \times \text{number of houses}) \times \%_{\text{cavity wall}} \times \%_{\text{un-insulated cavity wall}}$$

equation 3.2 estimation of the total un-insulated cavity wall surface in the Netherlands

The estimated un-insulated cavity wall surface then becomes just over 201 million m^2. When compared to the total un-insulated roof surface given by VROM (2009, pp. 32), it turns out to be almost double that surface (109 million m^2 against 201 million m^2.) The 109 million m^2 is the total surface of both flat and pitched roofs, where the 200 million m^2 is only cavity wall surface.

3.3 Estimation of the amount of insulating material

According to Meeusen (2006, pp. 13) the thickness of the air cavity in a cavity wall is between 5 and 7 cm. To get an estimation of the amount of insulating material needed to fill the empty cavity walls in the existing housing sector, the outcome of equation 3.2 must be multiplied with this thickness. If an air cavity of 5 cm thick is used throughout the Netherlands, over 10 million m^3 of insulating material is needed. This is equal to 41% of the German insulation production of 2005 (Wecobis, 2011). This is of course a rough estimation. Apart from that, filling up existing cavity walls will only reduce the energy needed for space heating minimally. This can also be seen in figure 3.3.1, where the R_c-values of a cavity wall filled with either mineral wool flocks or EPS pearls are depicted. None of the materials is able to meet the requirements for cavity walls ($R_c = 2.5\ m^2 \cdot K/W$) set by the building decree of 2003. If a new technology material such as aerogel granules is used, filling an air cavity of 6 cm is enough to reach the current 2003 building decree requirements. However, the 2012 building decree requires a higher thermal resistance of 3.5 $m^2 \cdot K/W$, which with aerogel granules is achieved after insulating a cavity wall of 9 cm (see figure 3.3.1). As mentioned above, air cavities larger than 7 cm are unlikely to be encountered in existing houses, which means that even with a material like aerogel, filling an existing cavity wall provides only a small improvement. According to Rockwool (2010, pp. 2), the thermal resistance of a cavity wall without any insulation is 0.35 $m^2 \cdot K/W$ (indicated by the dotted line in figure 3.3.1).

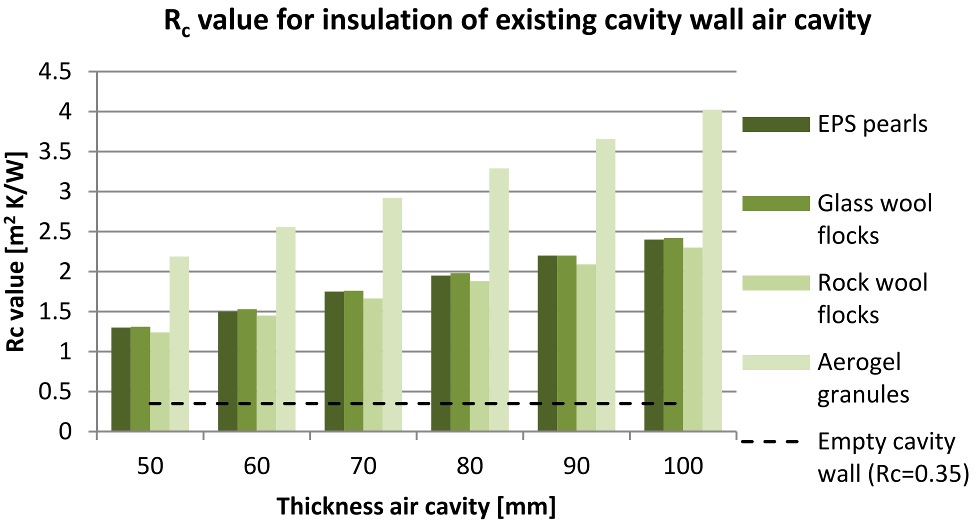


figure 3.3.1 R_c-value for filled cavity walls (Knauf, 2011; Isover, 2001; Rockwool, 2010; Innodämm, 2011)

3.4 Passive house renovation

As can be seen from figure 3.3.1, simple insulation of existing cavity walls by blowing insulating material into the air cavity is not reaching thermal resistance values higher than 2.5 $m^2 \cdot K/W$ with conventional materials. Therefore a more rigorous way of insulating houses is needed that reduces the energy requirement for space heating to a lower value, such as required for Passive houses. A way of doing this is to renovate houses. The current rules towards renovation are, according to the 2003 building decree, that if a building is fully renewed (renovated) it must meet the requirements set for insulation for newly constructed houses (Bouwbesluit, 2003b). When a building is renovated because of its poor energetic performance, there are also other options that exceed the requirements (and therefore also the energy reduction) of the building decree. A concept that has its own energetic and thermal insulation requirements for renovation is the Passive house concept.

3.4.1 Description of a Passive house

The Passive house concept has been developed by Wolfgang Feist and Bo Adamson. In their own words, a Passive house can be best described as: "A Passive house is a building in which a comfortable interior climate can be maintained without active heating and cooling systems" (Passive House Institute, 2011a). Before a house can be called a Passive house, it has to meet certain criteria. The criteria for a newly built residential Passive house are (Passive House Institute, 2011b):

- **Specific space heating (and cooling) demand (Q_H): ≤15 kWh/m^2a**
  Or heating load ≤10 W/m^2
- **Total specific primary energy demand (Q_p) ≤120 kWh/m^2a**
  (incl. household electricity)
- **Air tightness n_{50} (pressure result test) ≤0.6 /h**

The criteria above are almost impossible to accomplish within existing houses. New Passive houses can be dimensioned and designed with the criteria in mind. For existing houses this is not possible. Therefore, another set of criteria specifically aimed at existing buildings is devised to cope with the lower degree of design freedom. The criteria for Passive house renovations are as follows (Passive House Institute, 2011c):

- **Specific space heating (and cooling) demand: Q_H≤25 kWh/m^2a**
- **Total specific primary energy demand Q_p≤ 120 kWh/m^2a + ((Q_H - 15 kWh/(m^2a)) * 1.2) (incl. household electricity)**
- **Air tightness (pressure result test) 0.6/h ≤ n_{50} ≤ 1.0/h**

In order to reach these criteria, Feist and Schnieder (2010, pp.144-145) define four components that form the basis of a Passive house:

1. **Excellent thermal insulation, including the avoidance of thermal bridges, and low window heat losses**

The excellent thermal insulation translates into the value listed in table 3.2. These values apply to the elements of the building envelope. On top of these criteria, criteria are also set for cold bridges: $\Psi < 0.01$ W/m·K. Cold bridges exist in areas where the thermal insulation is breached, usually around window casings and so called building knots, where floor and wall are connected. A method to see where cold bridges might occur is to try and draw the thermal insulation layer of the building in one go. Everywhere the pen or pencil has to be lifted from the paper because the thermal insulation layer cannot continue there, can be seen as a cold bridge. Glazing used in Passive houses should have solar heat-gain coefficients (the amount of sunlight that enters via the glass) >50% (de Boer et al, 2009; Passive House Institute, 2011).

table 3.2 level of insulation for elements of the building envelope (De Boer et al, 2009)

Building element	Passive house level of insulation
Wall, roof and floor	$6.5 < R_c < 10$ [$m^2 \cdot K/W$]
Window casings, doors	<0.8 [$W/m^2 \cdot K$]
Window glazing	<0.8 [$W/m^2 \cdot K$]

To reach the values shown in table 3.2, a thick layer of insulating material is needed. For wall, floor and roof elements this thickness can be as much as 30 cm when conventional insulating materials like mineral wool or EPS are used. With the use of insulating materials with a low thermal conductivity (e.g. hard foam panels) this thickness can be reduced to approximately 20 cm (Passipedia, 2011).

The U-value for glazing and glass casings are achieved by using triple glazing in casings suited with a thermal interruption to prevent cold bridges. An example of such a window casing fitted with triple glazing can be seen in figure 3.4.1. The casing is made out of wood, but can also be produced out of aluminium, plastic or a combination of materials. In figure 3.4.1, the thermal interruptions are indicated with circles. These interruptions are made out of hard foams and diminish the heat flow through the casing, giving it a low U-value (0.78 $W/m^2 \cdot K$ for the casing of figure 3.4.1). The triple glazing makes the window relatively heavy, which is something that has to be taken into consideration during the design of the building. Wall structures have to be strong enough to carry to weight of the windows.

figure 3.4.1 Passive House window and casing adjusted after (Overbeek, 2010)

2. A very airtight building envelope

The second basic component of a Passive house is an airtight building envelope. An airtight building envelope is obtained by very detailed construction by which air gaps and air leakage can be prevented. All joints and gaps should be covered or filled so that no air can leak out through the building's construction. What this means in practice can be seen in figure 3.4.2, where all the joints between the OSB (wooden) panels are sealed with tape. Behind the panels is insulating material covered with a foil of which the seams are also taped to prevent air leakage. To test the air tightness of a Passive house, a so called blower door test is performed. For this test the door of the house is replaced by a door with a large fan, capable of over pressuring the house. The building is brought to an over pressure of 50 Pa. At that pressure, the house may only leak 60% of its volume per hour. This is often expressed as the n50 value, which should be lower than 0.6 ($n_{50} \leq 0.6$). Today's common practice values for new houses in the Netherlands lie between 2.32 - 2.63 at 50 Pa (De Boer et al, 2009; Strom et al., 2006).

figure 3.4.2 sealing joints with tape (DWA, 2009)

3. A ventilation system with highly efficient heat recovery

Because of the air tightness of a Passive house, ventilation is vital to guarantee a comfortable indoor climate. However, to prevent ventilation heat losses, balanced ventilation is used. Balanced ventilation works by blowing fresh air into a room and extract the 'old' air. Fresh air originates from outside the house and is filtered before it enters the system. The balanced ventilation system is equipped with a heat recovery system: a counter flow heat exchanger in which extracted warm air from inside the house is used to preheat the fresh air coming from outside. There is no strict rule for the efficiency of the heat recovery unit. The Passive House Institute however indicates that the efficiency should be above 80% (Passive House Institute, 2011a). According to De Boer et al. (2009, pp. 16) systems with higher efficiencies are available (up to 95%) and could therefore also be used.

4. The passive use of solar energy

The idea behind Passive houses is to insulate houses to such an extent that there is almost no need for additional space heating. By orientating the building to the South, solar heat is used optimally. Because of the thick insulation layer, the heat from the sun is preserved within the house. During days with little sunshine or very low temperatures, it is sufficient to heat the incoming fresh ventilation air to keep the building at a comfortable temperature (Feist and Schnieder, 2010).

Internal heat gains

Another important factor for Passive houses are the internal heat gains. Electrical appliances such as televisions, computers, refrigerators and others produce heat. This heat also contributes to the heat balance of a Passive house. The importance of internal gains can also been in a typical annual energy balance of a Passive house, presented by Feist and Schnieder (2010, pp. 146). In figure 3.4.3, this energy balance is depicted.

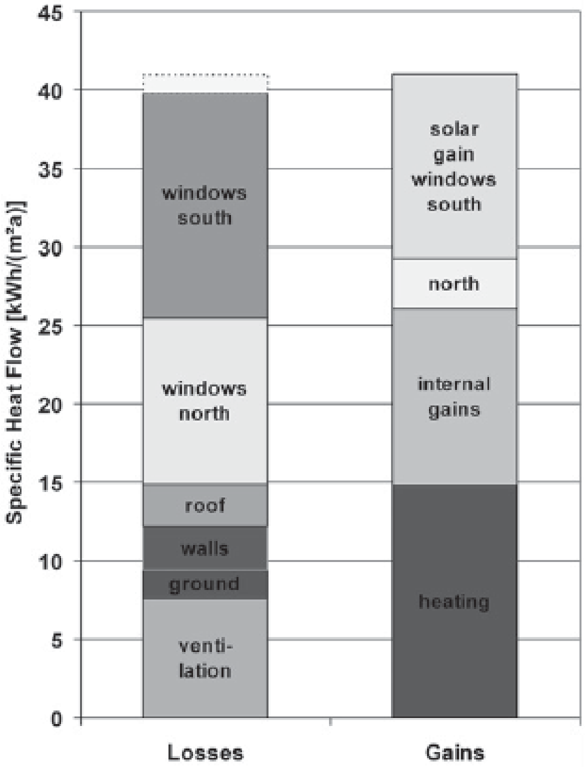


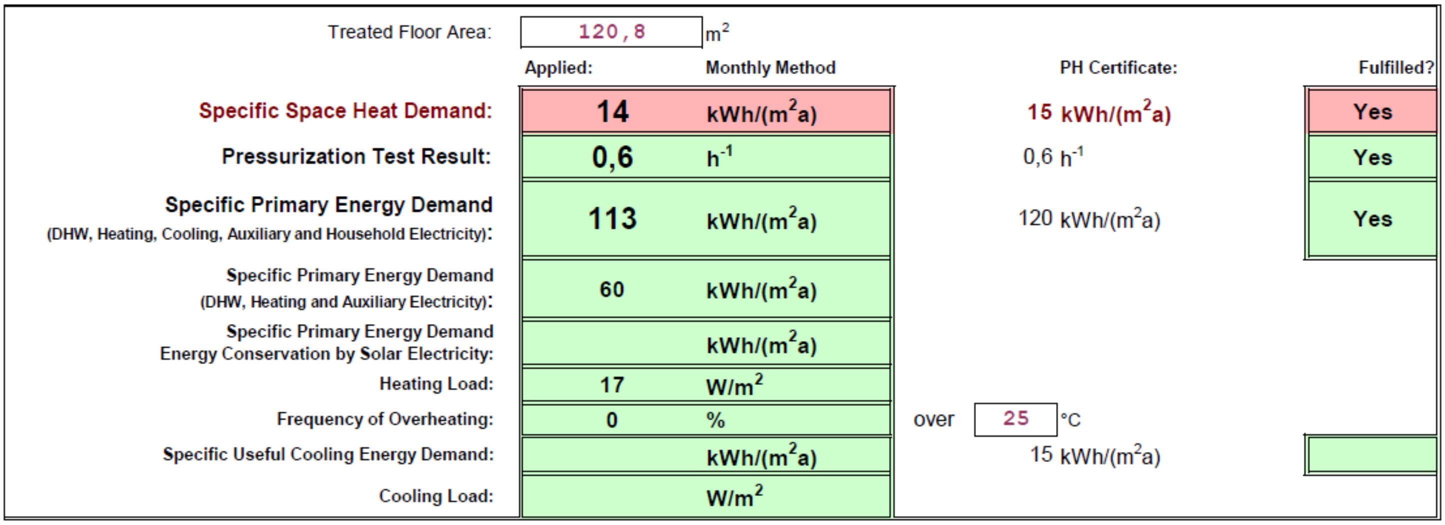
figure 3.4.3 typical energy balance of a Passive house (Feist and Schnieder, 2010)

Passive house certification

If the Passive house criteria are met, they result in a low energy building. To be sure that this building can be considered a Passive house, the Passive house Institute hands out certificates. In the heat annual heat balance of figure 3.4.3, the first of three requirements for the Passive house certificate can be found: the net annual energy for heating may not exceed 15 kWh/m^{2}a (54 MJ/m^{2}a). Next to this, the heating load must be lower than 10 W/m^2. Another requirement not mentioned earlier is that the primary energy demand for heat, hot water and household electricity does not exceed 120 kWh/m^{2}a (432 MJ/ m^{2}a). The final requirement is the criterion for ventilation: n_{50}<0.6.

Passive house Planning Package 2007 (PHPP)

To determine whether a Passive house meets the criteria, a design tool has been developed by the Passive House Institute. The air tightness is tested with a blower test, of which the results determine whether the criteria are met or not. For all other factors the PHPP is used. PHPP is a Microsoft Excel based calculation method in which the entire Passive house can be modelled. When all the information (U-values, surfaces, cold bridges etc.) is entered into PHPP, it shows if the criteria are met. In figure 3.4.4 the Passive house verification sheet is shown. All the information and building details entered into PHPP have an effect on this part of the calculation. The column on the right shows whether the criteria for a certification are met. If all the cells show a "yes" the certification process can begin. PHPP is used as the calculation method for both new Passive houses and Passive house renovations.



Treated Floor Area:	120,8	m^2		
	Applied:	Monthly Method	PH Certificate:	Fulfilled?
Specific Space Heat Demand:	14	kWh/(m^{2}a)	15 kWh/(m^{2}a)	Yes
Pressurization Test Result:	0,6	h^{-1}	0,6 h^{-1}	Yes
Specific Primary Energy Demand (DHW, Heating, Cooling, Auxiliary and Household Electricity):	113	kWh/(m^{2}a)	120 kWh/(m^{2}a)	Yes
Specific Primary Energy Demand (DHW, Heating and Auxiliary Electricity):	60	kWh/(m^{2}a)		
Specific Primary Energy Demand Energy Conservation by Solar Electricity:		kWh/(m^{2}a)		
Heating Load:	17	W/m^2		
Frequency of Overheating:	0	%	over 25 °C	
Specific Useful Cooling Energy Demand:		kWh/(m^{2}a)	15 kWh/(m^{2}a)	
Cooling Load:		W/m^2		

figure 3.4.4 Passive house verification sheet (De Boer et al., 2009)

3.5 Passive house renovation

The four components of the Passive house concept mentioned in section 3.4.1 also apply to houses subjected to renovation. As mentioned in section 3.4, the criteria for new houses are too strict for existing houses. In this section the main requirements for Passive house renovation are described.

Insulation

Since thermal insulation forms the basis for Passive houses, almost no changes are made to the criteria of table 3.2. Only the U-value for windows has changed: $U_{w,installed} \leq 0.85$ W/m^2·K. This is the average value of all windows installed in the house, which means that certain windows can have higher U-values, as long as the average stays below 0.85 (Passive House Institute, 2011c).

Air tightness and ventilation

Air tightness is another component hard to achieve in existing buildings. Therefore the criterion for air leakage of $n_{50} \leq 0.6$/h is set as a 'target value'. The limit value is set to $n_{50} \leq 1.0$/h. For ventilation, a balanced system with heat recovery is again needed. The efficiency of the heat recovery unit has to be higher than 80% ($\eta_{HR,eff} \geq 80$ %). An additional demand is that electrical efficiency of the ventilation system is less or equal to 0.45 Wh/m^3 (Passive House Institute, 2011c).

As can be seen in the criteria list in section 3.4, the heating load criterion has been taken of the list for Passive house renovations. This is due to the fact that the renovated house already has a heating system in place that does not use air as fluid. The heating load of 10 W/m^2 is a result of the ventilation flow rate (1 m^3/h per m^2) and its maximum inlet temperature of 55˚C (Feist and Schnieders, 2009). If the existing radiators in a house are used, the maximum heating load does therefore not apply. The specific space heating demand has been raised to 25 kWh/m^{2}a (90 MJ/m^{2}a). This is due to the orientation of the existing building and the lower air tightness. As a comparison, the energy needed for space heating for a 125 m^2 terraced house is given in figure 3.5.1. The first bar represents the average energy needed for space heating in houses in the Netherlands. The second bar indicates the energy use for space heating of a terraced house with an EPC equal to 0.8. The third and fourth bar represent the energy needed for space heating for a house that has been renovated to the Passive house level and a newly constructed Passive house respectively.

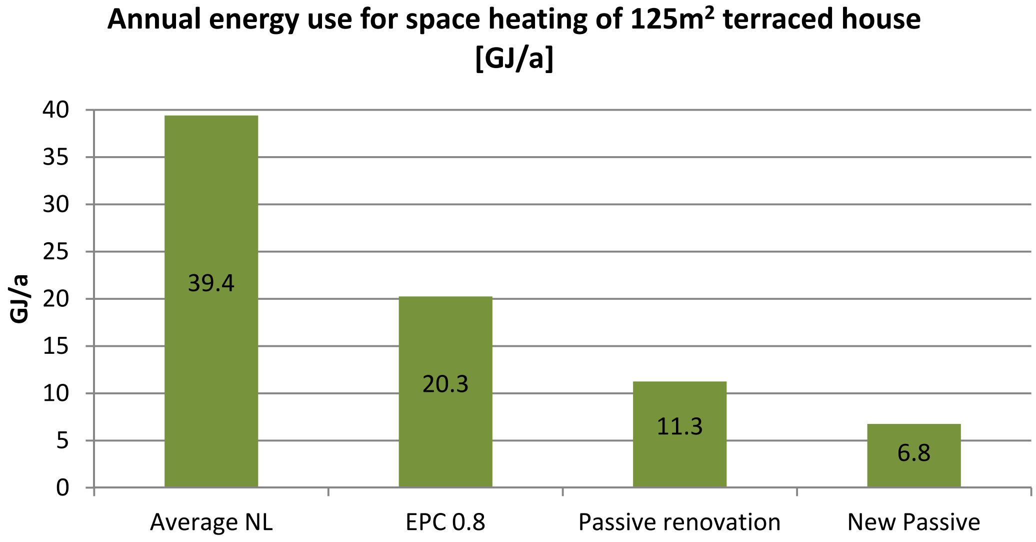


figure 3.5.1 annual energy use for space heating, 125m^2 terraced house (Agentschap NL, 2012; Boonstra, 2006)

3.6 Methods of insulating existing houses to the Passive house level

In this section, methods of insulating existing houses to the Passive house level will be discussed based upon two projects that serve as an example. The focus will lie upon the practical use of the insulating materials to reach the Passive house level. The renovated houses both stem from a different time period and thus different building methods were applied. Next to that, the houses belong to different sectors (private ownership and rented houses). The differences between the project result in diverse solutions for the Passive house renovation.

The first project is the renovation of 246 terraced houses in the Dutch city of Roosendaal. In district ‘De Kroeven’ social housing corporation Aramis (part of AlleeWonen) decided to renovate part of their houses to the Passive house level. A special aspect of this renovation was the fact that the residents were able to stay within their homes during the renovation. The houses themselves were built in the late fifties – early sixties and were constructed with cavity walls and purlin roofs[12]. For the renovation, the houses in the district were split into two different projects: “505” (134 houses) and “506” (112 houses) both with different solutions for insulating the existing cavity walls. The ground floor of the houses is made out of concrete with a crawl space underneath.

The second project is a Passive house renovation at the “Sleephelling” in Rotterdam, where 14 privately owned apartments were created inside existing buildings. In the corner building, 16 rented apartments were created for social care. Although the number of apartments renovated is relatively low, the project itself is very interesting, because the apartments are situated inside 9 buildings (built in 1903), of which the front facade is protected cityscape, which means that the look of the facade has to remain intact and may not be altered. The rear facade was not a protected cityscape, which means that alterations to this facade were possible. Both facades are constructed out of solid brickwork. The roofs of the buildings consisted of partial flat and partial rafter roof constructions. Also in this project, the ground floor was made out of concrete. After the renovation, the apartments were sold to private owners.

3.6.1 Roof insulation

To reach the needed thermal resistance value for the roofs in the De Kroeven, Aramis has used the almost the same principle for all the 246 houses. A new roof was prefabricated to replace the old roof. To support the weight of the new roof, a new support beam was needed. The larger weight of the roof is a result of the thickness of the insulating material: 40 cm of blown in cellulose flocks. As a finish layer, either PVC (505) or roof tiling (506) is used. To lower the energy demand and to enlarge the use of solar energy, the roofs were fitted with solar water heaters. After removing the old roof and installing a new support beam, the new prefabricated roof was lifted into place by a crane (Van Rede, 2011). The process of replacing the roofs was done per house, as can be seen in figure 3.6.1, where the new roofs are already fitted to the houses on the right, but not yet to the houses on the left.

figure 3.6.1 roof placement on a terraced house in district ‘De Kroeven’ in Roosendaal (Brink Climate Systems, 2011)

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[12] see appendix A for a description if common construction methods in the Netherlands

For the renovation of roofs at the "Sleephelling", different roofs shapes had to be insulated. To keep the original pitched rafter construction visible (an aesthetic demand), mineral wool was used on both the in- and outside of the roofs, resulting in a R_C of 5.3 $m^2 \cdot K/W$. The flat roof elements were insulated with mineral wool on the in- and outside as well, resulting in a R_C of 8.8 $m^2 \cdot K/W$. The roof terraces were insulated from the inside to a R_C of 7.4 $m^2 \cdot K/W$. Insulating on the inside was possible because of the high ceilings in the old buildings (Vellekoop, 2011; Stiching PassiefHuis Holland, 2011). All insulating materials were fitted on site; almost no prefabricated elements were used. In figure 3.6.2, a sketch of how the roof of the Sleephelling looks, is depicted.

figure 3.6.2 sketch of the Sleephelling roof (Adjusted after Stichting PassiefHuis Holland, 2011)

3.6.2 Facade insulation

The houses in both projects in De Kroeven were constructed with cavity walls. The method of renovation used for project 505 was however different from project 506. For project 505 the outer wall of the cavity wall construction was removed. A trench was dug around the houses, to widen the foundation of the houses. On this widened foundation, a prefabricated timber frame construction was placed, which was mounted against the remaining wall. Like the roofs, the timber frame facade elements were also insulated with cellulose flocks, resulting in walls with an R_c of 9 $m^2 \cdot K/W$. In figure 3.6.3 and figure 3.6.4 the removal of the outer wall and the placement of the new facade element can be seen. The new facade element was finished with dry cladding system with a layer of slates, to provide a modern look (Van Rede, 2011).

figure 3.6.3 removing the outer wall (Stichting PassiefHuis Holland, 2011)

figure 3.6.4 fixing the wood timber frame elements (VDM, 2011)

The houses in De Kroeven had already been retrofitted with insulating material as can be seen in figure 3.6.3, where a layer of rock wool flocks is clearly visible between the inner and outer wall and between the bricks on the ground. From figure 3.3.1 it is clear that thermal resistance values obtained from filling up a cavity wall do not come close to the Passive house insulation values. However, such a filling does contribute if the insulating method of project 506 is used.

For the method of project 506, the cavity wall is kept intact. To insulate the walls to the Passive house level, a wet render system[13] is used. Polystyrene blocks are adhered to the existing outer wall of the cavity wall. The blocks are finished with a render which could be painted later on. By combining the existing cavity wall with a layer of polystyrene of approximately 27 cm thick, an R_c-value of 8.5 $m^2 \cdot K/W$ is achieved. The finished situation for both projects can be seen in the figures below (Van Rede, 2011).

figure 3.6.5 before and after renovation De Kroeven (Van der Werf, 2011; VDM, 2011)

Facade insulation at the Sleephelling

At the De Kroeven district there were no strict restrictions on the appearance of the facade. In Rotterdam however, the appearance of the front facade and all its details had to be kept at all times. This meant that the front facade could only be insulated on the inside by placing an insulated wall behind the facade, with a loss of living space as a consequence. This wall was insulated with a 30 cm thick layer of rock wool, which was covered with foil in order to achieve the air tightness. The achieved thermal resistance of the facade is 7.5 $m^2 \cdot K/W$. How this looks in practice, can be seen from figure 3.6.6 in which the tape used to cover the seams for air tightness can be seen. For this project, the so called ‘box in box’ method was used. This method considers the existing building to be a box, in which by means of insulation, another airtight and thermal resistant box is created. The windows of the front facade for example could not be changed because of their protected state. Consequently, the existing windows and casing could not be changed or moved. To insulate the windows, new double glazed windows were placed in the newly built insulated wall behind the existing facade. This way a form of triple glazing is achieved without affecting the appearance of the original facade (Vellekoop, 2011; VILLA*NOVA*, 2009).

figure 3.6.6 inside insulation with taped up seams (Woonstad Rotterdam, 2011)

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[13] see appendix A for a full description if a wet render system

The rear facade of the buildings was not a protected cityscape, which made insulating this facade easier; insulating on the inside of the buildings was not necessary. The walls of the buildings are made out of solid brickwork, which makes them suitable for insulation on the outside of the facade. Similar to project 506 in Roosendaal, polystyrene blocks were adhered to the facade. The blocks are 35cm thick, which together with the brick wall and render finish resulted in a thermal resistance of 10 $m^2 \cdot K/W$. To get an impression of the size/thickness of the EPS blocks, a picture of the adhered blocks to the existing wall can be seen in figure 3.6.7.

figure 3.6.7 mounting of EPS block to existing wall (Woonstad Rotterdam, 2011)

The final result of the renovation of both the front and rear facade can be seen in figure 3.6.8 and figure 3.6.9 respectively. The white rear facade used to be in the same style as the front facade, a red brick appearance. After the renovation and the insulation of the facade, the render finish provides a smooth white surface, equal to the facade of project 506 in district De Kroeven (see figure 3.6.5). Besides the smooth finish layer, other options are also available that provide options to mimic the original facade. With the use of so called stone strips and decorative elements, the original facade can be mimicked on top of the adhered insulation (Sto, 2011). In figure 3.6.9 another important design feature of the buildings can be seen: the solar water heaters on the roofs of the buildings. In the original situation, the flat roofs in between the triangular rooftops was not present. This meant that placing solar water heaters on the roof would prove to be hard, because of the shadow casted by the adjacent roofs. To solve this problem, the flat roofs were constructed in between the pitched roofs, creating more space inside (see also figure 3.6.2) and eliminating the placement problem for the solar water heaters (Vellekoop, 2011; VILLA*NOVA*, 2009).

figure 3.6.8 front facade after renovation (VILLA*NOVA*, 2009)

figure 3.6.9 rear facade after renovation (VILLA*NOVA, 2009)*

3.6.3 Floor insulation

Both the buildings in Roosendaal and Rotterdam have a concrete ground floor. To insulate the floors, two different methods are used. In both project 505 and 506 in Roosendaal, the crawl space underneath the concrete floor was 40 cm high. At first the plan was to cover the bottom of the concrete floor with spray-on polyurethane (PUR) foam. However, the height of the crawl space was too low to for a person to actually go into the crawl space and apply the foam. As a result, the crawl space is completely filled by blowing in EPS pearls. This 40 cm of EPS pearls alone already has a thermal resistance of approximately 8.5 $m^2 \cdot K/W$. An additional advantage of EPS pearls over PUR foam is that all the sewage and water piping run through the crawl space. If a problem would occur with one if the pipes, the EPS pearls can easily be extracted from the crawl space to solve the problem. When PUR foam is sprayed onto the bottom of the floor, all pipes will also be covered in solid foam which is hard to remove (Van Rede, 2011).

In the Sleephelling renovation, the existing concrete ground floor is insulated by covering the top side of the floor with polyisocyanurate (PIR) panels. Over the PIR panels, a covering floor was poured, resulting in a thermal resistance of 5.3 $m^2 \cdot K/W$ for the floor.

From the sample projects above it can be concluded that there are many options of renovation an existing building to the Passive house level. Even in difficult situation like the Sleephelling where the front facade had to remain intact, Passive house levels of insulation were achieved. Both project received the Passive house renovation certificate, indicating that not only the insulation, but all other criteria were met as well. In both projects balanced ventilation was applied to the buildings. The channels for the ventilation in the Sleephelling were concealed in the ceilings. In the houses in district De Kroeven the channels were concealed in casings. There is a sufficient amount of practical solutions to renovate existing building to a Passive house level.

3.6.4 Estimation of insulating material need for Passive house renovation

What can be concluded from the previous section furthermore is that renovation according to a Passive house level leads to thick insulation layers. In the projects mentioned above, layers of insulating material range from 27 to as much as 40 cm of insulation. An estimation of the insulation materials needed to renovate all not insulated wall surface to the Passive house level can be made, according to the method of section 3.3. Instead of calculating with the thickness of the air cavity in cavity walls, the thickness of 27 cm needed for the renovation of project 506 in De Kroeven is used. For this estimation, the solid brick walls are also taken into account, because these walls can also be insulated by adhering insulating materials to the outside of the walls. Solid brick walls represent approximately 68.8 million m^2. According to VROM (2009, pp. 34), 70% of this surface was not insulated in 2006. This results in a not insulated solid brick wall surface of just over 48 million m^2. If the assumption is made that both the cavity wall and brick wall surfaces are insulated with a 27 cm thick layer of insulation, the total volume of insulation material needed to renovate the mentioned wall surfaces to the Passive house level is approximately 67.3 million m^3. This is equal to 275% of the German insulation production in 2005 (WECOBIS, 2011). If only the cavity wall surface would be insulated to Passive house insulation levels, this would require approximately 54 million m^3 of insulating material. In figure 3.6.10, these amounts are depicted graphically.

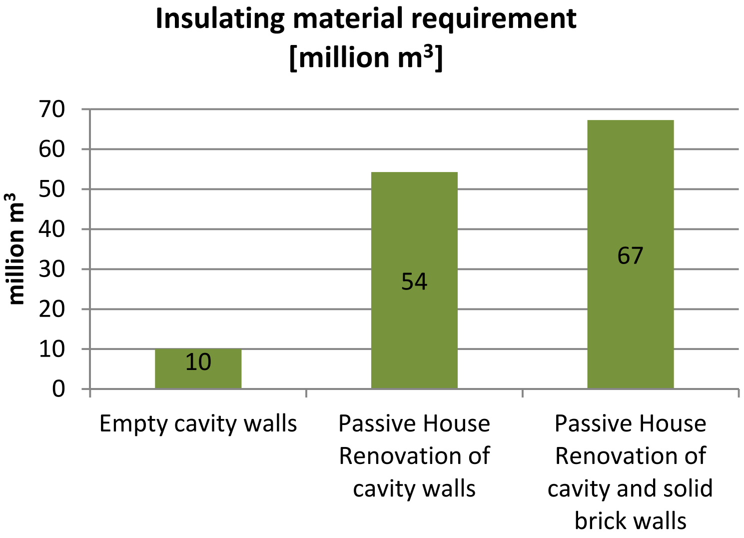


figure 3.6.10 Insulating material requirement for the filling of empty cavity walls and the Passive house renovation of cavity and solid brick walls

A comment that should be made here is that the estimation is done based upon the degree of insulation. Almost all buildings in the Netherlands do not meet the Passive house criteria. If all these buildings would be renovated to Passive house levels over time, the demand for insulating materials would be even larger.

3.7 Discussion

Regulation

Considering the low energy efficiency for space heating in the existing housing stock and increase in energy performance regulation, Passive house renovation provides a valuable solution that has proven itself in practice. For newly constructed houses, the EPC-values will decrease over time. Lower EPC-values result in thicker thermal insulation, as is shown in table 3.1. In 2015, the EPC for new buildings will be lowered to a value of 0.4, which can only be reached with R_c-values equal to the Passive house values (see table 3.2). Apart from insulation, technical installations such as boilers and ventilation units also need to be very energy efficient (Vreeman and ten Bolscher, 2009). With the Passive house concept, a solution is provided in which both construction and installation aspects are integrated. In a study done for Agentschap NL, Nieman (2011, pp. 12-36) provides a complete list with constructional as well as installation related renovation solutions. In this study, Nieman (2011, pp. 9) mentions the Passive house concept as an integral concept, in which all the elements for low energy renovation are present. As mentioned in 3.1, the EPC norm and calculation will be renewed in 2012. For Passive houses this is good news, because the current calculation program is not able of coping with the high Passive house criteria. The input for air tightness for example is limited in the program, which means that the calculation is made with an incorrect value for the air tightness. If an EPC calculation is done for Passive houses with the current methods, this will result in an EPC between 0.3 and 0.5 (Boonstra, 2006; de Boer et al, 2009).

Age of dataset

For the estimation of the renovation potential, data from 2006 is used. In the years after 2006, houses were also fitted with insulation, which causes the estimation from section 3.6.4 to be too high. According to Gerdes (2010, pp. 26), the number of existing houses which were insulated in the period 2006-2009 is in line with the trend from 2001-2006 (depicted in figure 3.2.3). If this trend is extrapolated to 2011, this would result in 59.4% of the wall surface in the existing housing stock to be insulated. In the period 2006-2010 approximately 240 thousand new houses have been constructed. Because of the energy performance norm and the requirements of the building decree it can be assumed that all of these houses are insulated. This extra insulated building stock also causes an increasing amount of insulated houses. Nonetheless, the number of un-insulated houses and thus the renovation potential remains high.

Difference in degree of insulation for wall, floor, roof and glazing insulation

In figure 3.2.3 a large difference is found between the degree of insulation of different building elements. Roof insulation and double glazing have the largest share. For glazing, this has to do with the subsidies on double glazing which have been in place for several years and the fact that it can be done relatively easy. For roof insulation, this is also the case. 78% of the houses in the Netherlands has a pitched roof, which can easily be fitted with insulated by the residents themselves (VROM, 2009). For wall and floor insulation subsidies can also be obtained, but here the practical limitations for the inhabitants are larger. Insulating an existing cavity wall by injection of flocks or foam can only be done by third parties, because it requires special machinery. For floor insulation, inhabitants need to have enough height in the crawl space. If the crawl space is not high enough or often flooded by ground water, insulating the ground floor is difficult.

Financial aspects

Agentschap NL has published a factsheet with success factors for energy efficient construction of new houses and renovations. On this factsheet, six important tracks are distinguished of which the first is 'Technology'. As mentioned in section 3.6, there is a variety of practical solutions for renovating to a Passive house level. This indicates that for Passive house renovation, the first track is covered. Another track mentioned on the factsheet is 'financing and costs' (Agentschap NL, 2011a). The costs for renovating to the Passive house level are hard to estimate. To renovate a row house similar to the ones in De Kroeven along the standards of the building decree, Agentschap NL (2011b, pp. 41) gives a cost estimate of €8,980. This cost estimate assumes that the installations are already up to date and that only the building envelope needs insulation. According to van Rede (2011) the Passive house renovation of houses in De Kroeven was around 20% higher than the costs for normal renovation. This small increase was because of subsidies granted to the project and the size of the project. The costs for the renovation of the Sleephelling in Rotterdam were much higher due to its small scale and the protected cityscape status of the front facade. Per apartment, the involved parties lost around 100k€ (Vellekoop, 2011). Due to the fact that the rent for the inhabitants in Roosendaal was only raised by 65€ (the estimated energy savings), the project in Roosendaal is also losing money (van Rede, 2011). Both Vellekoop and van Rede however do not consider the projects as failed. On the contrary, the projects were done as pilot projects from which a lot of knowledge on Passive house renovation was obtained.

4 Saving potential of cavity wall insulation

To see how much energy could be saved by insulation, an estimation is made by looking at the savings potential of un-insulated cavity walls. Since cavity walls represent around 78% of the wall surface in the Netherlands (VROM, 2009), it is interesting to estimate the possible energy savings of insulating the un-insulated cavity wall surface.

4.1 Energy savings

For the estimation of the energy saving potential of insulating existing walls, the results of section 2.6 and section 3.2 are combined. As mentioned in section 3.2, 40% of the cavity wall surface in the Netherlands is not insulated. For this estimation, complete filling of the empty cavities is assumed. According to Blok (2009, pp. 115) the annual heat loss through a wall can be calculated with the use of degree-days, as is shown in equation 4.1.

$$Q_a = k \times A \times D \times (24 \times 3600 s/day)$$

equation 4.1 annual heat loss through a wall

In which:

Q_a = annual heat loss through wall [J]
A = surface area of the wall [m^2]
K = average heat transfers coefficient of the wall [$W/m^2 \cdot K$]
D = the number of degree-days [˚C-days]

In the Netherlands, the number of degree-days is approximately 3000 (SenterNovem, 2007b). In figure 3.3.1, the achievable R_c-values of filling existing cavity walls are shown, together with the R_c-value of an empty cavity wall. The K-value in equation 4.1 is the inverse of the R_c-value. By using 1 m^2 in the calculation, the annual energy loss per m^2 is obtained. As a basic assumption for the calculation, a cavity wall with an air cavity thickness of 5 cm is used, equal to the method of section 3.2. From the material selection of section 2.2, it is clear that aerogel is too expensive to be a feasible option for the filling of cavity walls. Mineral wool flocks and EPS pearls on the other hand are affordable materials with a reasonable thermal conductivity. Besides this, both EPS and mineral can be recycled at the end of their useful lifetime. Once more, EPS is split in white and gray EPS. In figure 4.1.1, the effect of insulating an existing cavity wall on the annual energy loss through the wall is shown graphically. It can be seen that although filling a cavity wall does not lead to high R_c-values (see figure 3.3.1), it does have a large effect on the annual energy heat flow through the wall.

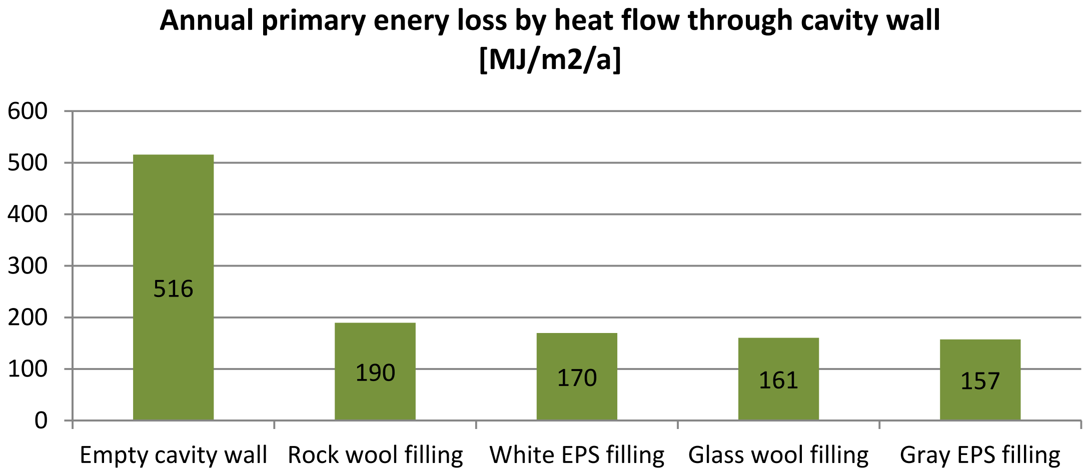


figure 4.1.1 annual energy loss of cavity wall with 5 cm air cavity empty and filled [MJ/m^2]

With the annual savings known per m^2 of insulated cavity wall, it is interesting to see whether or not the reduction in energy loss compensates for the energy needed for the production of the materials. To do so, the results of the cradle-to-grave LCA assessment of section 2.6 are used. The results of table 4.1 show that the annual energy saving due to insulation of the cavity wall is much greater than the energy needed for the production of the materials. For the calculations, it is assumed that all the households have a central heating system with an individual boiler which has an efficiency of 97% (Blok, 2009). In reality, only 87% of the Dutch households have an individual boiler, of which 84% is a so called HR-Boiler (high efficiency boiler) (Agentschap NL, 2012). Because of these assumptions, the estimation is conservative and the energy saving in practice could be even higher. In the table, the values for Passive house renovation of the cavity wall are also presented for the minimum (R_c = 6.5 m^2·K/W) and 'maximum' (R_c = 10 m^2·K/W) insulation criteria. The results from table 4.1 show that the energy needed for the production of the materials is subordinate to the energy saved by the reduction in heat loss through the wall. Only for rock wool the energetic payback time is higher than 1 year, but this is for an R_c of 10 m^2·K/W. The higher values for rock wool are explained by the fact that rock wool flocks have a high density (75 kg/m^3) when blown in the cavity wall combined with a low thermal conductivity (0.044 W/m·K) (Rockwool, 2012). As a comparison: glass wool has a blown in density of 30 kg/m^3 and a thermal conductivity of 0.034 W/m·K (Knauf, 2008). The reason for this is that glass wool is more resilient against deformation, which keeps the fibre structure intact (van Rooy, 2011). For the filling of cavity walls, flocks are assumed for mineral wool and loose pearls for EPS. In the case of Passive house renovation, cavity products made out of the materials are assumed (similar to section 2.3).

table 4.1 energetic payback time of insulation by filing the existing air cavity and Passive house renovation

Material	Mass of material needed [kg/m^2]	CED of the insulating material [MJ]	Primary energy saved per year [MJ/m^2]	Energetic payback time [Year]
Filling of the existing air cavity (5cm)				
Rock wool (R_c = 1.24)	3.8	66.6	326	0.20
White EPS (R_c = 1.41)	0.9	47.6	346	0.14
Glass wool (R_c = 1.50)	1.5	51.0	355	0.14
Gray EPS (R_c = 1.53)	1.0	52.5	358	0.15
Passive house renovation, R_c = 6.5 m^2·K/W				
Rock wool	18.2	324	476	0.68
White EPS	4.4	231	476	0.49
Glass wool	6.8	230	476	0.48
Gray EPS	4.2	220	476	0.46
Passive house renovation, R_c = 10 m^2·K/W				
Rock wool	28.6	508	489	1.04
White EPS	6.9	367	489	0.74
Glass wool	10.6	361	489	0.74
Gray EPS	6.6	346	489	0.71

If the cavity walls are renovated to the minimum Passive house insulation level of R_c = 6.5 m^2·K/W instead of filled, an even larger amount of energy can be saved per m^2 of wall surface. This is shown in figure 4.1.2, in which also the 'maximum' Passive house insulation level is depicted. In the bar diagram, the energy savings for the insulation standards of the current building degree (2003) and the future building decree (2012) are also shown.

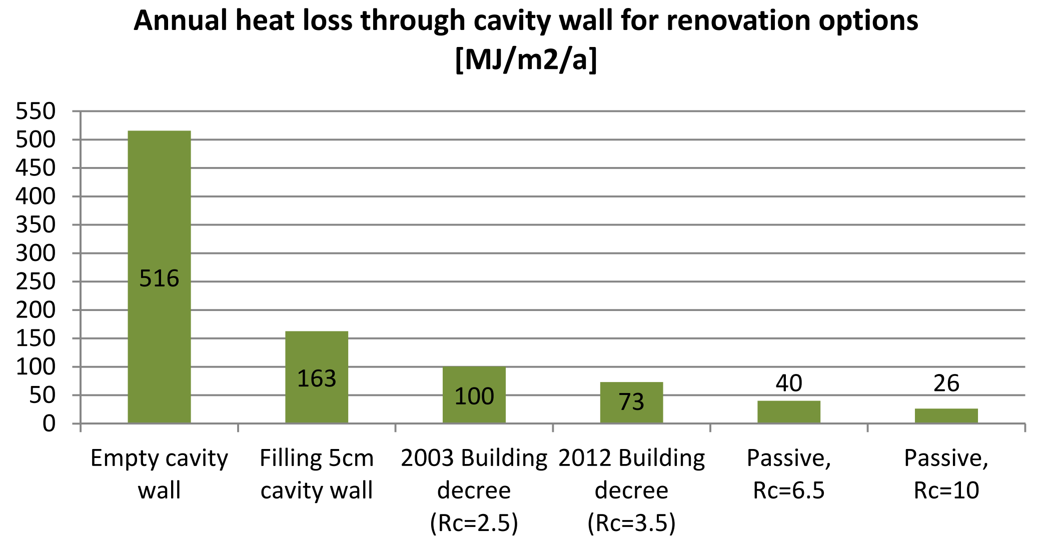


figure 4.1.2 annual energy loss for common practice and Passive house renovation options of an empty cavity wall

Although there is no such thing as a ‘maximum’ R_c-value, it is not very useful to strive for higher values, since the heat loss will only decrease minimally, whereas the thickness of the insulation becomes impractical. This is because of the K-value from equation 4.1, which is $1/R_c$. The calculation of the K-value can be seen as a limit that approaches zero, but will never become zero. So, R_c-values higher than 10 $m^2 \cdot K/W$ will only have a minor effect, as is shown in figure 4.1.3. The shape of the graph in figure 4.1.3 shows a resemblance with the bar diagram from figure 4.1.2. From the graph it can be concluded that filling the current empty cavity walls will already result in a large energy savings, because the R_c-value will increase from 0.35 $m^2 \cdot K/W$ to about 1.3 $m^2 \cdot K/W$.

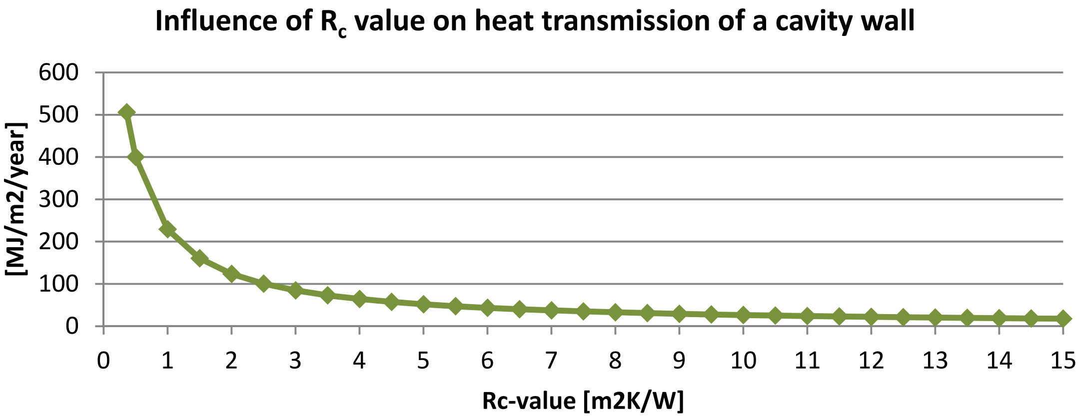


figure 4.1.3 influence of R_c-value on heat transmission through a cavity wall

Annual energy savings for the Netherlands

At the end of section 3.2 the un-insulated cavity wall surface in the Netherlands was estimated to be approximately 200 million m^2. With this estimation and the results from table 4.1, an estimation of the energy saving of filling this 200 million m^2 surface with insulating material can be made. For this estimation, it is assumed that every material in table 4.1 has an equal market share, so each material is assumed to insulate 25% of the cavity wall surface. Next to that, it is assumed that all the empty cavity walls have an air cavity of 5cm and that the cavity walls are structurally solid enough to be filled. The lifetime of the filled cavity wall is assumed to be 50 years, which means that the CED for the materials is discounted over 50 years.

A similar estimation is also done for renovation of cavity walls to the minimum Passive house insulation level of $R_c = 6.5\ m^2 \cdot K/W$. In practice, this value can only be reached by adhering insulating materials to the outer cavity wall or by removing the outer wall, filling the air cavity and replacing the outer wall. For this estimation, the latter solution is used. However, only the CED of the materials is taken into account, because no data was available on the CED of the construction process of cavity wall renovation. In figure 4.1.4, the estimated energy saving potential is depicted. For just the filling of the existing cavity walls, an annual energy saving of 69.4 PJ can be achieved. This is equal to 11% of the current energy used for space heating. A renovation to Passive house levels will achieve an even higher saving of almost 95 PJ/year. Over the lifetime of 50 years, renovation to the Passive house level will save almost 1260 PJ more than just filling the cavity walls.

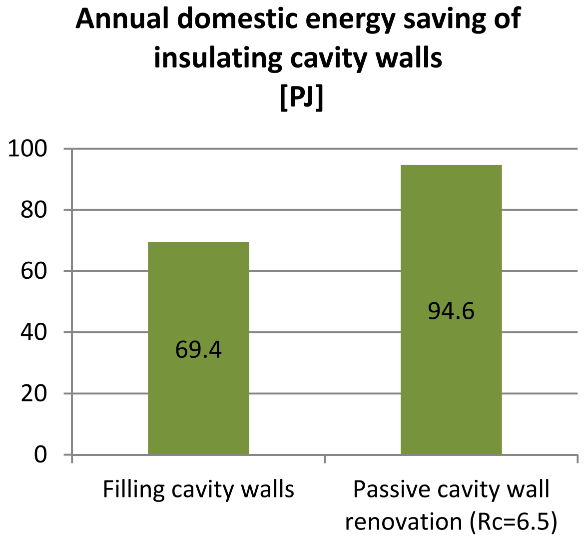


figure 4.1.4 annual energy saving of insulating cavity walls in the Netherlands

4.2 GHG-emissions saving potential

In section 2.6 the GHG-emissions of the insulating materials are presented. With these emissions and the saved primary energy per m^2 cavity wall of table 4.1, the avoidance of GHG-emissions can be calculated. For the calculations, the emission factor for Dutch natural gas is used: 56.6 $kgCO_2$/GJ (Zijlema, 2010). The results of combining the results from section 2.6 and table 4.1 are given in table 4.2. From the table it is clear that insulating cavity walls will results in a large avoidance of GHG-emission. Only for rock wool and white EPS in a $R_c = 10$ $m^2 \cdot K/W$ cavity wall it will take longer than one year before the emissions from the production of the materials are compensated. Equal to table 4.1, the materials are taken into account, not the process of insulating itself, which for Passive house renovation could have a significant contribution.

table 4.2 GHG-emissions from materials and avoided by reduction in heat loss

Material	Mass of material needed [kg/m^2]	GHG-emissions of the needed material [$kgCO_2$ eq]	Avoided GHG-emissions [$kgCO_2$ eq/m2/a]
Filling of the existing air cavity (5cm)			
Rock wool ($R_c = 1.24$)	3.8	5.6	18.3
White EPS ($R_c = 1.41$)	0.9	4.1	19.5
Glass wool ($R_c = 1.50$)	1.5	3.0	20.0
Gray EPS ($R_c = 1.53$)	1.0	4.2	20.2
Passive house renovation, $R_c = 6.5$ $m^2 \cdot K/W$			
Rock wool	18.2	27.1	26.4
White EPS	4.4	19.7	26.5
Glass wool	6.8	13.6	26.6
Gray EPS	4.2	17.7	26.6
Passive house renovation, $R_c = 10$ $m^2 \cdot K/W$			
Rock wool	28.6	42.5	26.8
White EPS	6.9	30.9	27.1
Glass wool	10.6	21.4	27.3
Gray EPS	6.6	27.7	27.1

In figure 4.2.1 the GHG-emissions of several insulating options for a square meter of cavity wall are depicted graphically. Again, a great improvement is found for only a small amount of insulation. Just the filling of an empty cavity wall can provide an emission reduction of 20 $kgCO_2$ eq/m^2 cavity wall. According to Milieucentraal (2012), the price of insulating an existing cavity wall by filling it with insulating material is around €16.50 per m^2. This means that for an existing cavity wall, the avoidance costs range from 0.82 to 0.9 €/$kgCO_2$ (or 820 – 900 €/tCO_2). For renovating to the Passive house level no costs were found. This is because the Passive house renovation has not been applied on a large scale, but also because every Passive house renovation is tailored to the specific case.

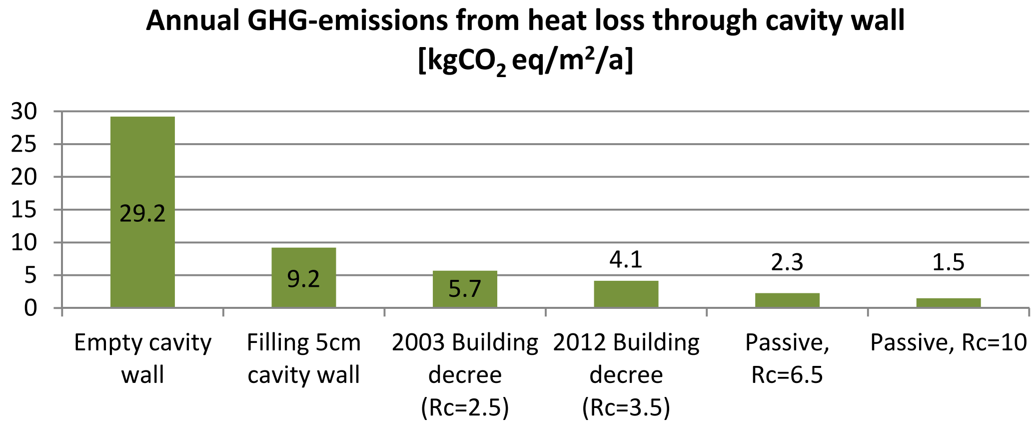


figure 4.2.1 annual GHG-emissions for different insulating options and levels of insulation

Annual GHG-emission reduction for the Netherlands

With the avoided GHG-emission per m^2 cavity wall from table 4.2 and the un-insulated cavity wall surface in the Netherlands, an estimation can be made of the total GHG-emissions reduction in the Netherlands. Like for the energy saving potential, it is assumed that all the empty cavity walls haven an air cavity of 5 cm and are structurally solid to be filled with insulating material. Also, a lifetime of 50 years is assumed for the materials, which is also the period over which the emissions from the material production are discounted. In figure 4.2.2 the GHG-emission reduction of filling an empty cavity wall and Passive house renovation of the cavity wall are shown.

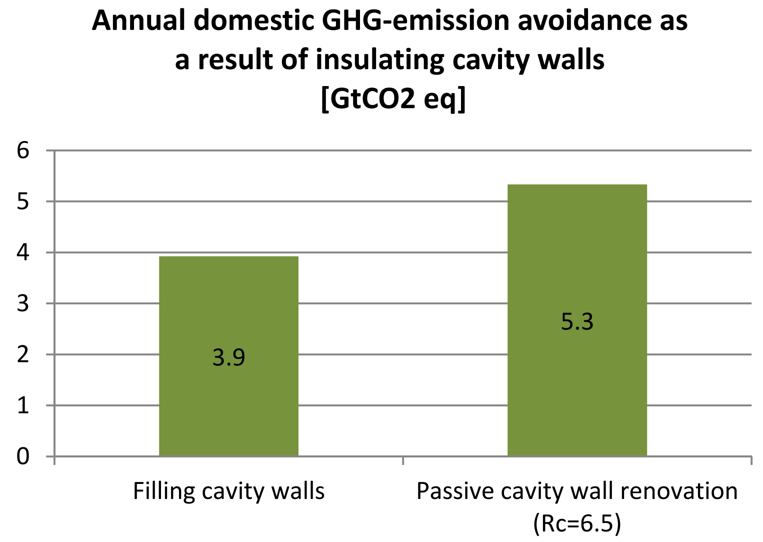


figure 4.2.2 annual GHG-emission avoidance as a result of cavity wall insulation

From this section as well as the previous section it can be concluded that the renovation of cavity walls in the Netherlands can lead to a significant emission- and energy reduction. Just the filling of empty cavity walls with insulating materials will result in large savings. However, renovation of cavity walls to a higher R_c-value (2012 building decree or Passive house level) is preferable. This is because of the lifetime of (over) 50 years, in which a large extra saving can be achieved. Besides the cavity walls, also the other elements of a building's envelope should be insulated, which will result in even higher energy- and GHG-emission savings.

4.3 Discussion

EPS and mineral wool CED

For the filling of the cavity walls with EPS pearls and mineral wool flocks the CED data of section 2.6 is used. The CEDs presented there for EPS include thermoforming the loose pearls into a panel. Mineral wool flocks on the other hand are produced by shredding newly produced glass and rock wool into flocks, which is an extra production step. This means that for EPS the CED contains an extra process, whereas for rock- and glass wool a part of the production process is missing. Also, the process of blowing in the pearls or flocks into the cavity wall is not taken into account. Using the CED from section 2.6 is nevertheless appropriate. For EPS, the thermoforming of the pearls into blocks is only a fraction of the CED. According to EUMEPS (2011, pp.7) 85% of the CED of EPS can be allocated to the raw material production. The remaining 15% is allocated to the expanding the granules with steam, indicating that thermoforming the expanded pearls into blocks or panels is not a major contributor to the CED.

As for rock- and glass wool, the melting of diabase/basalt or cullet, the spinning of fibres and the production of the binder are the main contributor to the CED (Kellenberger et al, 2007; IBU, 2011a). Shredding the wool blankets has no effect on these processes and it is unlikely that shredding the wool will have a significant energy consumption compared to those processes. Blowing the flocks and pearls into the cavity wall will also consume energy. Unfortunately, no data is available on the energy consumption of this procedure. It is assumed that the process of blowing in the flocks and pearls does not have a significant energy consumption and thus has no significant effect on the CED of the materials. The same reasoning can be followed for the GHG-emissions of the materials which are closely related to the CED.

Passive house renovation energy

Passive house renovation on the other hand might have a large effect on the material CED. Especially when the outer wall of an existing cavity wall structure is removed and replaced by new masonry. The found values for Passive renovation could therefore be too positive. However, the amount of energy that is saved during the lifetime of the building is large. This means that the energy that is saved by Passive house renovation over the lifetime of the building will certainly compensate for the energy of the production and the placement of the insulating materials. Furthermore, in the estimation above, only the heat loss through walls is taken into account. For Passive house renovations however, the energy saving in practice is even higher because of the advanced ventilation system, the building's air tightness and the high level of insulation of the other elements of the building envelope. These factors are not taken into account in the estimation above, but will definitely increase the energy and emission savings.

Boiler efficiency

The assumed boiler efficiency of 97% is relatively high. This high efficiency together with the assumption that all households have an HR-Boiler ensures a conservative estimation. In reality, efficiencies will be lower. Also, the efficiency of the heat distribution and heat emission are not taken into account, which could also lower the overall efficiency of the central heating system in a house. The 97% efficiency is also assumed for Passive house renovation. This can be done, because most of renovated houses maintain their gas connection. Special systems are used in such renovations that combine the domestic hot water supply, the heating of the incoming ventilation air or heating via the existing radiators. In De Kroeven such a system was used. The efficiency of the system used is approximately 97%. (Brink climate systems, 2011).

5 Conclusion

Application of the Passive house concept

As was shown in section 3.1, the energy efficiency requirements for both new and existing buildings will continue to rise. In 2020 all newly built houses should be ‘near zero energy buildings’. The Passive house concept is a major leap in the direction of nearly energy zero buildings. By also renovating the existing building stock to a Passive house level, a significant amount of energy can be saved with a large GHG-emission reduction as a result. Passive house renovation has proven to work in practice as was shown in section 3.6. Chapter 3 and 4 show that there are no technical, environmental or health reasons to not apply the Passive house concept. However, the economic aspects speak against its application, as can be concluded from both the discussed sample projects in Roosendaal and Rotterdam.

Best materials

From the LCA assessment of chapter 2 it can be concluded that there is no such thing as ‘the best insulating material’. This means that there is no univocal answer to the main research question posed in section 1.1. The reason for this is the fact that the use of insulating materials is application specific, as can be seen in table 2.2. Nonetheless, when reasoning from an environmental or health point of view it can be concluded that certain materials do perform better than others. The overall environmental impacts for PUR/PIR products are much higher than the overall impacts of PF-foam. However, the environmental impacts and CED during production are more than made up for by the savings potential provided by the insulating materials during a 50 year lifetime. Therefore, it is important to focus on the end-of-life options for the materials. Especially when Passive house renovation will be applied on a large scale in the near future, the use of materials with end-of-life options such as recycling or reuse is preferable. For both PUR/PIR products and PF-foam this is not the case. Both materials are hard to recycle at this moment, due to lacking means. At present, hemp- and flax wool are also hard to recycle because of their support fibres. This combined with their relatively high environmental impacts and CED, makes these materials unattractive for large scale use. Hemp- and flax wool are however subjected to improvement, which is illustrated by the development of a cornstarch-based PLA support fibre instead of polyester.

This leaves three materials: EPS, glass wool and rock wool. Apart from GHG-emissions, EPS performs better from an environmental point of view than the mineral wools. As for the CED, the required energy for EPS is higher for the production phase, but almost equal to the mineral wools in a cradle-to-grave analysis. Both EPS and mineral wool have a large application range, as is shown in table 2.2. This large application range combined with the low price of the materials has resulted in a large market share. Both EPS and mineral wool have multiple end-of-life options, which is crucial for materials used on a large scale. On top of that, the recycling of these products is already common practice an can be done on a large scale. The downside of EPS and mineral wool are the health aspects. The fire retardant HBCD used in EPS only represent 1% of the material. However, considering the large future demand as estimated in section 3.6.4, this 1% could turn out to be a huge quantity. Next to this, the recycling of EPS containing HBCD in the future is subjected to discussion and thus insecure. A replacement for HBCD is needed.

For glass- and rock wool such a replacement has already been found in the form of a bio-based binder. The use of the bio-based binder has eliminated the formaldehyde emission from the material, without affecting the recyclability of the wools. Until now, Knauf is the only producer using this binder, but other producers are likely to follow. Health aspects that will remain regardless of the used binder are the irritating effects of the fibres. These effects mainly occur during the placing of the insulating materials and can be prevented by implementing safety measures and applying an airtight building envelope that prevents fibres from entering the building.

Considering the fact that mineral wool and EPS: are used already on a large scale, have no exceptional high CED or environmental impacts, have multiple end-of-life options, have health aspects for which solutions already exist or are likely to be found in the near future, it can be concluded that EPS and mineral wool are ‘the best’ materials for application in Passive house renovation. Besides this, both mineral wool and EPS can also be used in common insulation of existing structures, such as cavity walls. The high savings potential combined with the increasing standards set by regulation (e.g. building decree and EPC), calls for materials with straightforward application, low environmental impacts, low costs and proper end-of-life solutions. Therefore, EPS, glass wool and rock wool can be considered the best materials available today for both Passive house and common renovation.

Recommendations for further research

The application of the Passive house concept has proven to be costly for renovation projects. It should be investigated (and designed) how the Passive house concept can be applied in a cost-effective way. It could be that prefab elements can provide smart structural solutions against a feasible price.

For now, EPS and mineral wools are the best choice when considering the end-of-life phase of the materials. However, the insulation value of these materials is not so high compared to other insulating materials. For materials such as PF-foam and PUR/PIR the recycling options should be widened and enhanced. Recycling of these products could result in a lower price and lower environmental impacts. Research should be conducted on further development of recycling options of PF-foam and PUR/PIR insulating materials.

As mentioned above, a replacement needs to be found for HBCD. This flame retardant is bio-accumulative and forms a health hazard. Research is needed to find a replacement for HBCD that does not affect the properties of EPS. The decision on the recycling of EPS containing HBCD in the future should not be awaited, but solutions must be found in any case.

The innovative materials shown in table 2.1 and appendix B are promising. The thermal conductivity of vacuum insulation panels and aerogel could drastically reduce the thickness of walls that are currently needed for Passive houses. Future research should focus on optimizing the production process of these materials, so that the prices of these materials come down.

To improve the recycling of insulating materials, take back schemes could form an option. Producers could for instance pay a certain amount of money for insulating material that is returned to them after the useful life of the insulation material. It should be investigated what the effect of a financial incentive is, or whether it is better to choose for a different type of return policy.

6 References

Adviesbureau Nieman, 2011. *Technieken in de bestaande bouw.* [online] Available at:<http://www.agentschapnl.nl/sites/default/files/bijlagen/Technieken%20in%20de%20bestaande%20bouw%20mei%202011.pdf> [Accessed: 11 January 2012]. (in Dutch).

Agentschap NL, 2011a. *Concepten EPC 0.4 Energieprestatie Nieuwbouw – EPN*. [online] Available at: <http://www.agentschapnl.nl/programmas-regelingen/concepten-epc-04-energieprestatie-nieuwbouw-epn> [Accessed 18 January 2012]. (in Dutch).

Agentschap NL, 2011b. *Succesfactoren energiezuinige nieuwbouw en renovatie.* [online] Agentschap NL. Available at: <http://www.agentschapnl.nl/sites/default/files/bijlagen/Succesfactoren_NB_en_Renovatie.pdf> [Accessed: 11 January 2012]. (in Dutch).

Agentschap NL, 2011c. *Voorbeeldwoningen bestaande bouw.* [online] Agentschap NL. Available at: <http://www.agentschapnl.nl/content/brochure-voorbeeldwoningen-2011-bestaande-bouw> [Accessed: 11 January 2012]. (in Dutch).

Agentschap NL, 2012. *Energie data, gasverbruik naar woningtype 2009.* [online] Available at: <http://senternovem.databank.nl/> [Accessed: 19 January 2012]. (in Dutch).

Al-Homoud, M.S., 2005. Performance characteristics and practical applications of common building thermal insulation materials. *Building and environment*, Volume 40, Issue 3, pp. 353-366.

Blok, K., 2009. Introduction to energy analysis. Amsterdam: Techne Press. (in Dutch).

Boonstra, C., Clocquet, R., Joosten, L., 2006. Passiefhuizen in Nederland. Boxtel: Æneas. (in Dutch).

Brink Climate Systems, 2011a. *Passief renoveren de Kroeven Roosendaal.* [online]. Available at: <http://www.brinkclimatesystems.nl/getattachment/349a132c-a922-4798-a5fb-dc2f2063cf9e/Passief-renoveren--De-Kroeven--in-Roosendaal.aspx> [Accessed: 19 November 2011].

Brink Climate Systems, 2011b. *Passiefhuistoestel.* [online] Available at:<http://www.passiefhuismarkt.nl/custom/page_content/149.pdf> [Accessed: 24 January 2012]. (in Dutch).

Bos, U., Deimling, S., 2008*. Development of a complete biogenous insulating material – LCA results.* [online] Available at: <http://www.agroscope.admin.ch/aktuell/02720/02722/03985/04043/index.html?lang=de&download=NHzLpZeg7t,lnp6I0NTU042l2Z6ln1acy4Zn4Z2qZpnO2Yuq2Z6gpJCEdIN9gmym162epYbg2c_JjKbNoKSn6A--> [Accessed: 8 January 2012].

Bouwbesluit, 2003a. s5.1 (art. 5.3), [online] Available at :<http://vrom.bouwbesluit.com> [Accessed 30 August 2011]. (in Dutch).

Bouwbesluit, 2003b. s5.1 (art. 5.6), [online] Available at :<http://vrom.bouwbesluit.com> [Accessed 16 August 2011]. (in Dutch).

Bouwbesluit, 2003a. S1.4 (art. 1.6), [online] Available at :<http://vrom.bouwbesluit.com> [Accessed 12 October 2011] (in Dutch).

ChemSec (International Chemical Secretary), 2012. *Substitute it now list*. [online] Available at: <http://w3.chemsec.org/> [Accessed: 2 November 2012].

Concept Bouwbesluit 2012, 2011. s5.1 (art. 5.1), [online] Available at: <http://www.rijksoverheid.nl/bestanden/documenten-en-publicaties/besluiten/2011/05/02/ontwerpbesluit-bouwbesluit-2012/concept-bouwbesluit-2012.pdf> [Accessed 30 August 2011]. (in Dutch).

De Boer, B.J. et al., 2009. *Passiefhuis en EPN – Onderzoek naar de waardering van passiefhuizen volgens EPN en PHPP.* [online] ECN, DHV, Trecodome. Available at:<http://www.passiefbouwen.nl/documents/Passiefhuis_en_EPN_-_ECN_rapport_E--09-054.pdf> [Accessed: 16 November 2011].

DWA, 2009. *Sealing joint between OSB panels.* [image online] Available at: <http://www.dwa.nl/modules/Cataloger/Cataloger.Image.php?i=rijksmonument-middelburg_t_3_60_0.jpg&ac=11400> [Accessed: 17 November 2011].

Entrop, A.G., Brouwers, H.J.H., 2007. *Het Nationaal Isolatie Programma als voorloper van het energiebesparingsplan "Meer met Minder" voor de bestaande bouw.* In: IGS conference, 28 September 2007, Enschede.

European Association of EPS (EUMEPS), 2011. EPD: *Expanded Polystyrene (EPS) Foam insulation (with infra red absorber, density: 15kg/*m^3*).* [online] EUMEPS. Available at: <http://www.eumeps.org/show.php?ID=4743&psid=hmotjteo> [Accessed: 15 December 2012].

European Chemicals Agency (ECHA), 2012. *Candidate list table.* [online] Available at: <http://echa.europa.eu/web/guest/candidate-list-table> [Accessed: 2 November 2011].

Council Directive 2010/31/EU of 19 May 2010 on the energy performance of buildings (recast).

Feist, W., Schienders, J., 2009. Energy efficiency – A key to sustainable housing. *The European Physical Journal Special Topic,* 176, pp. 141-153.

Gerders, 2010. *Monitor schoon en zuinig: stand van zaken april 2010.* [online] ECN. Available at: <http://www.ecn.nl/docs/library/report/2010/e10042.pdf> [Accessed: 15 November 2011]. (in Dutch).

Guerra Santin, O., Itard, L., 2010. Verwarmingsenergie: van bewoners? *TVVL Magazine, Issue 4, pp. 14-18.*

Haas, M., 2008. *NIBE's Basiswerk Millieuclassificaties Bouwproducten deel 1.* NIBE: Bussum.

Hasselaar, B.L.H., 2004. *Vernieuwbare isolatie als duurzaam alternatief: een onderzoek naar de prestaties van vernieuwbare isolatiematerialen*. MSc thesis. Delft University of Technology. (in Dutch).

Hischier R., Althaus H.-J., Bauer C., Doka G., Frischknecht R., Jungbluth N., NemecekT., Simons A., Sutter J., Stucki M., Tuchschmid M., 2010 *Documentation of changes implemented in ecoinvent Data v2.1 and v2.2. ecoinvent report No. 16*. Swiss Centre for Life Cycle Inventories, St. Gallen.

Holzhey, L., 2011. *Questions on Thermo-hänf.* [e-mail] (Personal communication, 19 October 2012].

Innodämm, 2011. *Aerogel-Granulat Datenblatt.* [online] Innodämm. Available at: <http://www.innodaemm.de/download/daemmstoffe/Nanogel-Granulat.pdf> [Accessed: 25 October 2011]. (in German).

Institut Bauen und Umwelt (IBU), 2008. *EPD: Unkaschierte bzw. unbeschichtete kunstharzgebundene Steinwolle-Dämmstoffe.* [online] IBU Available at:<http://bau-umwelt.de/download/CY7e391a58X122ca87db45X30b3/IBU_EPD_DRW_2008112_D.pdf> [Accessed: 16 December 2012]. (in German).

Institut Bauen und Umwelt (IBU), 2009a. *Product caterogy rules* [online] IBU. Available at:<http://bau-umwelt.de/download/CY22ca6fa5X1269771fda0XYcbf/PCR_Schaumkunststoffe.pdf> [Accessed: 5 January 2012]. (in German).

Institut Bauen und Umwelt (IBU), 2009b*. EPS-Hartschaum (Styropor ®) für Wände und Dächer* [online] IBU. Available at:<http://bau-umwelt.de/download/C22bf5d3bX12622ef92abXY5c1e/EPD_IVH_2009311_D.pdf> [Accessed: 5 January 2012]. (in German).

Institut Bauen und Umwelt (IBU), 2010. *EPD: Werkmäßig hergestellte Polyurethan-Dämmstoffe* [online] IBU. Available at:<http://bau-umwelt.de/download/C185ba51dX12b427c9478XY4541/EPD_IVPU_2010112_D.pdf> [Accessed: 3 January 2012]. (in German).

Institut Bauen und Umwelt (IBU), 2011a. *EPD: climowool und SCHWENK Glaswolle* [online] IBU. Available at:< http://bau-umwelt.de/download/CYe743bdcX130d070d6f3X46f6/EPD_SDT_2011111_D.pdf?ITServ=CY32314dbX134c69ee4bbX28da> [Accessed: 3 January 2012]. (in German).

Institut Bauen und Umwelt (IBU), 2011b. *EPD: Mineralwolle mit ECOSE® Technology* [online] IBU. Available at:<http://bau-umwelt.de/download/C185ba51dX12b427c9478XY4541/EPD_IVPU_2010112_D.pdf> [Accessed: 3 January 20120]. (in German).

Isover, 2001. *Productblad spouwwol.* [online] Isover. Available at: <http://www.isover.nl/documentatieservice/productbladen/spouwwol/productblad.pdf> [Accessed: 16 November 2011]. (in Dutch).

Isover, 2008. *Renovatie en na-isolatie.* [online] Isover. Available at: <http://www.isover.nl/documentatieservice/themabrochures/renovatie-en-na-isolatie/brochure-renovatie-en-na-isolatie.pdf> [Accessed: 14 October 2011]. (in Dutch).

Isover, 2011. *Environmental declaration Mupan plus 110mm.* [pdf].

Jeeninga, H., Volkers, C.H. 2003. *Ontwikkeling van SAWEC. Een Simulatie en Analyse model voor verklaring en voorspelling van het Woninggebonden Energieverbruik en CO_2-emissie.* [Online] ECN. Available at: <http://www.ecn.nl/publicaties/PdfFetch.aspx?nr=ECN-C--03-067> [Accessed 14 September 2011].

Kellenberger, D., Althaus, J., Jungbluth, N., Künniger, T., Lehman, M., Thalmann, P., 2007. *Life cycle inventories of Building Products. Final report ecoinvent Data v2.0 No. 7.* EMPA Dübendorf, Swiss center for life cycle inventories, Dübendorf, CH.

Knauf, 2011. *Supapearl, Inblaasparels voor goede thermische na-isolatie van spouwmuren.* [online] Knauf. Available at: <http://www.knaufinsulation.nl/files/ki_nl/upload/documents/Supapearl.pdf> [Accessed: 16 November 2011]. (in Dutch).

Knauf, 2008. *Knauf Insulation Supafil: Verwerkingshandleiding spouwmuurisolatie.* [online] Available at: <http://www.knaufinsulation.nl/files/ki_nl/upload/documents/Verwerking%20Supafil.pdf> [Accessed: 23 January 2012]. (in Dutch).

Koivula, M. et al., 2005. Emissions from thermal insulations—part 2: evaluation of emissions from organic and inorganic insulations. *Building and environment*, Volume 40, Issue 6, pp. 803-814.

Lamers, M., 2011. *Interview on LCA and production aspects of EPS".* [Interview] (Personal communication, 23 November 2011). Martin Lamers is a technical advisor at Isobouw.

Lipworth et al., 2009. Occupational Exposure to Rock Wool and Glass Wool and Risk of Cancers of the Lung and the Head and Neck: A Systematic Review and Meta-Analysis. *Journal of occupational and environmental medicine,* Volume 51, Issue 9, pp. 1075 – 1087.

Lustig, C., Verlind, G., 2011. *Questions on Knauf glass wool and EPS products and LCA aspects*. [Interview] (Personal communication, 2 November 2011). Celine Lustig is Marketing Manager Benelux of Knauf insulation and Geert Verlind is a freelance technical advisor working for Knauf insulation.

Medard, M., 2012. *Questions on the high acidification values of Isover Glass wool products.* [e-mail] (Personal communication, 19 January 2012).

Meeusen, J., 2006. *Na-isolatie van spouwmuren.* M.Sc. University of Gent. (in Dutch).

Menkveld, M., Beurkens, L., 2009. *Duurzame warmte en koude in Nederland.* [online] ECN. Available at: <http://www.ecn.nl/docs/library/report/2009/b09014.pdf> [Accessed: 12 September 2011]. (in Dutch).

Meuwissen, E., 2012. *Questions on the LCA and health aspects for EPS.* [Phone call] (Personal communication, 17 December 2011). Edmar Meuwissen is the secretary general of EUMEPS.

Milieucentraal, 2012. *Gevelisolatie.* [online] Available at:<http://www.milieucentraal.nl/themas/thema-1/energie-besparen/isoleren-en-besparen/gevelisolatie/> [Accessed: 23 January 2012]. (in Dutch).

Ministry of public housing, environmental planning and environmental management (VROM), 2009. *Kernpublicatie WoOn Energie 2006.* [online] VROM. Available at: <www.rijksoverheid.nl/bestanden/documenten-en-publicaties/rapporten/2010/03/11/kernpublicatie-woon-energie-2006/kernpublicatie-20woon-20energie-202006.pdf> [Accessed: 9 November 2011]. (in Dutch).

Ministry of public housing, environmental planning and environmental management (VROM), 2010. *Cijfers over wonen, wijken en integratie 2010.* [online] VROM. Available at: <https://zoek.officielebekendmakingen.nl/blg-92956.pdf> [Accessed: 22 November 2011]. (in Dutch).

Molero, C., de Lucas, A., Rodríguez, J.F., 2006. Recovery of polyols from flexible polyurethane foam by “split-phase” glycolysis with new catalysts. *Polymer Degradation and Stability*, Volume 91, Issue 4, pp. 894-901.

Nederlands Normalisatie Instituut (NEN), 2001. *NEN-1068(NL) Thermische Isolatie van gebouwen – Rekenmethoden.* Delft: NEN. (in Dutch).

Nederlands instituut voor Bouwbiologie en Ecologie (NIBE, 2012a). *Omschrijving methode Milieuclassificitatie bouwproducten.* [online] Available at: <http://www.nibe.info/nl/methode> [Accessed: 12 January 2012].

Nederlands Instituut voor Bouwbiologie en Ecologie (NIBE, 2012b). *Questions on setup of database and database used* [Phone call] (Personal communication, 12 January 2012].

Novem, 2001. *Referentiewoningen bestaande bouw.* Delft: Drukkerij Meidam. (in Dutch).

Overbeek, 2010. *Passiefkozijn*. [online] Timmerfabriek Overbeek bv. Available at: <http://www.tifaoverbeek.nl/media/attachments/passiefkozijn_hout.pdf> [Accessed: 17 November 2011]. (in Dutch).

Papadopoulos, A.M., 2005. State of the art in thermal insulation materials and aims for future developments. *Energy and Bulidings*, Volume 37, Issue 1, pp. 77-86.

Papadopoulos, A.M., Karamanos, A., Avgelis, A. 2006.*Environmental impact of insulating materials at the end of their useful lifetime.* [online] Available at: <http://fibran.gr/sappek/docs/publications/article_4.pdf> [Accessed: 13 January 2012].

Passipedia, 2011. *Wärmeschutz im Gesamptkonzept.* [online] International Passive House Association. Available at: <http://passipedia.passiv.de/passipedia_de/planung/waermeschutz/waermeschutz_im_gesamtkonzept> [Accessed: 17 November 2011]. (in German).

Passive House Institute, 2011a. *What is a Passive House?* [online] Available at: <http://www.passivehouse.com/English/PassiveH.HTM> [Accessed: 16 November 2011].

Passive House Institute, 2011b. *Criteria for residential Passive Houses*. [online] PHI. Available at: <http://www.passiv.de/07_eng/03_cert/Gebaud/Cert_crit_Residential.pdf> [Accessed: 17 November 2011].

Passive House Institute, 2011c. *Criteria for Residential-Use Refurbished Buildings.* [online] PHI. Available at: <http://www.passiv.de/07_eng/03_cert/Gebaud/EnerPHit_Criteria_Residential_EN.pdf> [Accessed: 18 November 2011].

Rentier et al., 2005. *Jellema Bouwtechniek 4B Omhulling – Gevels.* 2nd ed. Utrecht/Zupthen: ThiemeMeulenhoff. (in Dutch).

Rijksinstituut voor Volksgezondheid en Milieu (RIVM, 2007). *Handboek binnenmilieu 2007*. [online] RIVM. Available at:<http://www.rivm.nl/milieuportaal/images/HB_Binnenmilieu_2007_compleet.pdf> [Accessed: 15 December 2012]. (in Dutch).

Rockwool, 2010. *Inblaasbrochure.* [online] Rockwool. Available at: <http://www.rockwool.nl/files/RW-BNL/documents/pdf/NL/brochures/Inblaaswolbrochure.pdf> [Accessed: 16 November 2011]. (in Dutch).

Rockwool 2012. *Questions on the blowing rock wool flocks into empty cavity walls.* [Phone call]. (Personal communication, 24 January 2012).

Schuurmans, A., 2011. *Interview on LCA and production aspects of Rockwool.* [Interview] (Personal communication, 23 November 2011). Agnes Schuurmans a chief engineer at Rockwool insulation.

SenterNovem, 2007a. *Voorbeeldwoningen bestaande bouw 2007.* [online] Senternovem. Available at: <http://www.woonbond.nl/downloads/Voorbeeldwoningen_bestaande_bouw_2007.pdf> [Accessed: 10 November 2011]. (in Dutch).

SenterNovem, 2007b. *Cijfers en tabellen 2007.* [online] Available at: <http://www.rijksoverheid.nl/bestanden/documenten-en-publicaties/brochures/2010/08/23/cijfers-en-tabellen-2007/39br2007g002-2008515-145713.pdf> [Accessed: 22 January 2012]. (in Dutch).

Spang, 2012. *Questions on the efficiency of incineration processes in EPDs set up by IBU.* [Phone call] IBU (Personal communication, 18 January 2012). Robert Spang is a Technical advisor at the IBU.

Spierings et al., 2004. *Jellema Bouwtechniek 03 Draagstructuur.* 2nd ed. Utrecht/Zupthen: ThiemeMeulenhoff, p128. (in Dutch)

Staatscourant, 2005. *Wijziging regeling bouwbesluit 2003.* Year 2005, edition 163. [online] Available at: <https://zoek.officielebekendmakingen.nl/stcrt-2005-163-p10-SC70834.pdf> [Accessed: 13 October 2011].

Statistics Netherlands (CBS), 2011a. Domestic Energy use 2006. [online] Available at: <http://statline.cbs.nl/StatWeb/publication/?DM=SLNL&PA=37281&D1=6-27&D2=a&D3=92&HDR=G2,G1&STB=T&VW=T> [Accessed 30 August 2011]

Statistics Netherlands (CBS), 2011b. Development of housing stock. [online] Available at: <http://statline.cbs.nl/StatWeb/publication/?DM=SLNL&PA=71527NED&D1=10&D2=a&VW=T> [Accessed 15 November 2011]

Statistics Netherlands (CBS), 2011c. Total number of sheep in the Netherlands. [online] Available at: <http://statline.cbs.nl/StatWeb/publication/?DM=SLNL&PA=80782NED&D1=440,538&D2=0-1,4,7,14,17,21-32,34-35,38-45&D3=10&HDR=T,G2&STB=G1&VW=T> [Accessed: 24 November 2011].

Statistics Netherlands (CBS), 2011d. Municipal waste, quantities. [online] Available at<http://statline.cbs.nl/StatWeb/publication/?DM=SLNL&PA=7467&D1=0-129,140-167&D2=0&D3=a&VW=T> [Accessed 24 November 2011].

Stichting PassiefHuis Holland, 2011. *Sleephelling te Rotterdam*. [online] Available at: <http://www.passiefhuis.nl/sleephelling_rotterdam.html> [Accessed: 19 November 2011]. (in Dutch).

Sto Isoned, 2011. *Brochures on product and systems for wet render systems*. [online] Available at: <http://www.sto.nl/86448_NL-Downloads-Brochures.htm> [Accessed: 21 November 2011].

Strom, I., Joosten, L., Boonstra, C., 2006. *Passive house solutions.* [online] DHV, EC. Available at: <http://erg.ucd.ie/pep/pdf/Passive_House_Sol_English.pdf> [Accessed: 17 November 2011].

Van den Hout A.F. et al., 2005. *Jellema Bouwtechniek 4A Omhulling – Prestatie-eisen/daken.* 2nd ed. Utrecht/Zupthen: ThiemeMeulenhoff. (in Dutch).

Van der Werf, E., 2011. *Bewonersbelangen bij renovatie en bewoonde staat.* M.Sc. Delft University of Technology.

Van der Woude, P., 2011. *Interview on the production process and LCA aspects of PF-foam*. [Interview] (Personal communication, 24 October 2011). Pierre van der Woude is a technical service consultant at Kingspan insulation.

Van Rede, R., 2011. *Interview on renovation to Passive House levels in district 'De Kroeven'.* [Interview] (Personal communication, 11 November 2011). Robert van Rede is a Technical project leader at Aramis.

Van Rooy, I., 2011. *Interview on LCA and production aspects of glass wool.* [Interview]. (Personal communication, 23 November 2011). Ivo van Rooy is a technical engineer at Isover insulation.

VDM, 2011. *Picture series of renovation de Kroeven.* [online] Available at: <http://www.vdm.nl/roosendaal_1.ashx> [Accessed: 21 November 2011].

Vellekoop, A., 2011. *Interview on renovation to Passive House levels at the "Sleephelling".* [Interview] (Personal communication, 14 November 2011). Arjan Vellekoop is a Project-manager at BAM Woningbouw.

VILLA*NOVA architecten, 2011. Passiefbouwen renovatie.* [online] Available at:<www.villanova-architecten.nl/files/211-Sleephelling-internet.pdf> [Accessed 21 November 2011]. (in Dutch).

Vreeman, L., ten Bolscher, H., 2009. Aanscherping EPC van 0,8 naar energieneutraal. *VV+,* May issue, pp. 292-299. (in Dutch).

WECOBIS, 2011. *Dämmstoffe, Marktanteile am Dämmstoffmarkt in Deutschland.* [online] Bundesministerium für Verkehr, Bau, und Stadtentwicklung & Bayerische Architektenkammer. Available at: <http://www.wecobis.de/jahia/Jahia/Home/Bauproduktgruppen/Daemmstoffe> [Accessed: 15 November 2011].

Woonstad Rotterdam, 2011. *Sleephelling: Eerste passiefhuis-renovatie in Nederland.* [online] Available at:<http://www.sto.nl/113232_NL-Beeldgalerieen-Sleephelling_brochure.htm> [Accessed: 21 November 2011]. (in Dutch).

Zijdeveld, C., 2011. *Interview on Passive Houses and their practical difficulties and opportunities* [Interview] (Personal communication, 4 November 2011).

Zijlema, 2010. *Berekening van de standaard CO2-emissiefactor aardgas t.b.v. kalenderjaar 2010 en emissiehandel 2011.* [online] Agentschap NL. Available at: <http://www.broeikasgassen.nl/docs/Zijlema%202010%20Berekening%20CO2-emissiefactor%20aardgas%20jaar%202010.pdf> [Accessed: 23 January 2012]. (in Dutch).

7 Appendices

A. Common building methods in the Netherlands

Wall constructions

- **Solid brickwork walls**

Solid brickwork walls are the oldest type of wall. A solid wall is nothing more than a brickwork wall. In the Netherlands, this type of wall was commonly used until 1920, after which the number of buildings with a cavity wall started to become dominant (Jeeninga and Volkers, 2003).

- **Cavity wall**

The cavity wall consists out of four layers: the inner wall (or inner leaf), a layer of insulating material (if build after 1975), an air layer followed by the outer wall (or outer leaf). The inner wall is usually constructed out of sand-lime bricks or concrete. For the outer wall, bricks are used. The thickness of the air cavity ranges from 0-6cm (Kooren, 200X). When there is no air cavity, the insulating materials should be covered with a foil, to protect it against moisture. Common insulation materials in cavity walls are panels made of mineral or glass wool and hard foams. The basic structure of the cavity wall is depicted in figure 1.

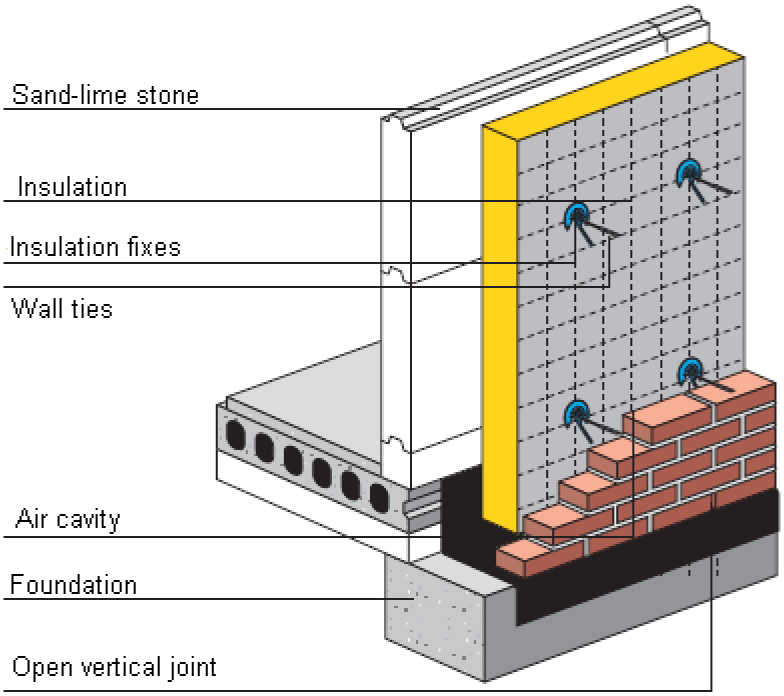


Figure 1, cavity wall (Adjusted from: Isover, 2008)

By connecting the inner and outer wall, the cavity wall becomes solid. This connection is made by (stainless) steel wall ties that also hold the insulating material into place. The cavity wall concept is used to prevent rainwater from seeping through the wall, which would otherwise create moist problems. When water hits the outer wall, the water can seep through the wall until it is stopped by the air cavity. At the bottom of the wall, some of the vertical joints between the brickwork are left open. These openings enable the water to leave the cavity wall and allow for ventilation. This causes the inner wall and insulating material to remain dry. In 1920, the use of a cavity wall was recorded into a model building code for municipalities. In the period 1995-1999 over 95% of the newly build houses were equipped with a cavity wall (Jeeninga and Volkers, 2003). This makes the cavity wall the most common building envelope in the Netherlands. A cavity wall is easy to recognize by its brick pattern and open vertical joints at the bottom, top and near window frames.

- **Dry cladding systems**

These systems consist of a solid interior wall constructed out of concrete, sand-lime bricks or other solids materials suitable for masonry. The interior wall can also be constructed out of (steel) beams, but this way of constructing the interior wall is often used for utility buildings and industrial buildings (Isover, 2008). On the outside of the interior wall, fixing rails (made of either wood or metal) are mounted, to which both the insulation materials and the cladding is fixed. With the use of either plastic or metal anchors, the insulating panels are mounted firmly against the wall. The cladding protects the interior wall and insulating material against rain (Kingspan, 2011a). Multiple materials can be used as cladding materials. In figure 2 the construction of a dry cladding system is depicted.

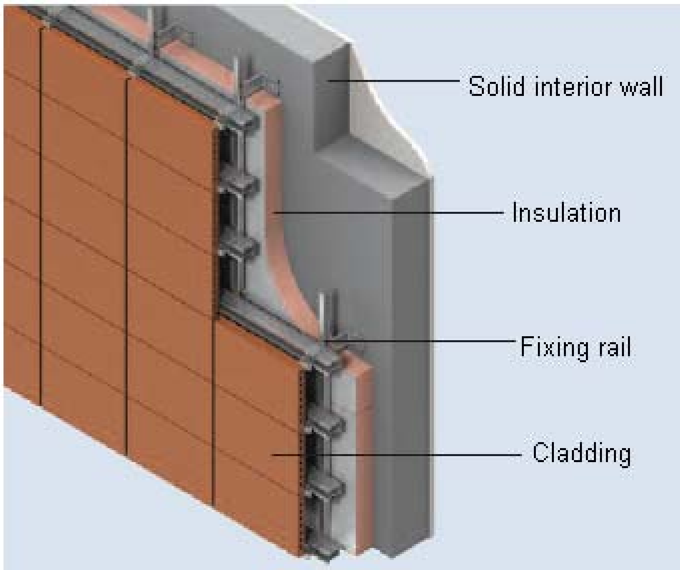


Figure 2, example of a dry cladding system (Adjusted from: Kingspan 2011a)

- **Wet render systems**

The basis of wet render systems is a concrete, brickwork or timber frame wall. Insulating material is directly fixed upon the wall with a fixing mortar and mechanical fixes (anchors). After fixing the insulating material, a render finish is applied over a layer of reinforcing mortar which has been reinforced with a mesh (Kuindersma, 2010). Figure 3 shows the different layers out of which the wet render system consists. The render finish and reinforcing mortar are all that separate the insulating material from weather influences. The render finish is however watertight and shelters the insulating material underneath from rainwater. Next to finish renders, other options are possible as well, which include options to mimic existing facades with the use of profiles and brick strips (Sto, 2011). An example of such can be seen in

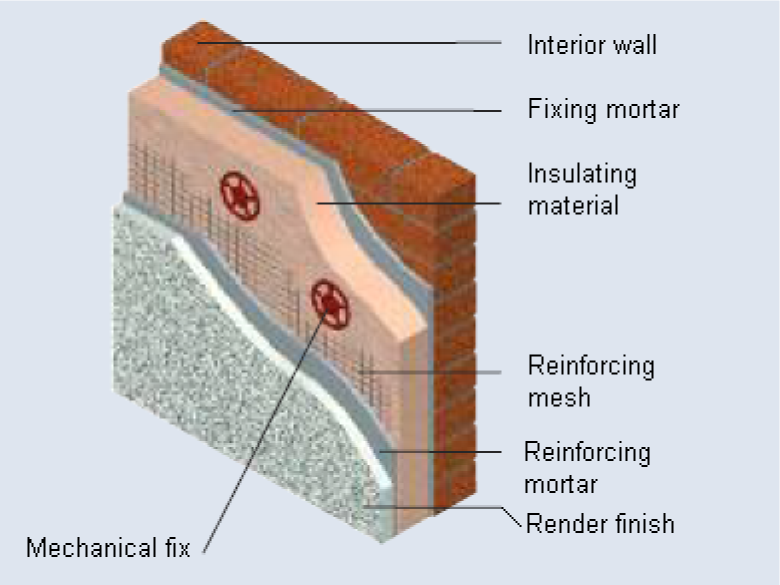


Figure 3, example of a wet render system (Adjusted from: Kingspan 2011b)

Figure 4 fixing the stone strips (Habavo, 2011)

Figure 5 finished result with stone strips (Habavo, 2011)

- **Timber frame construction**

The timber frame construction uses wooden beams for the support structure of the building. Figure 5 shows the construction of a timber frame construction. The timber frame construction also makes use of the cavity wall principle. This is done by creating an interior wall out of plasterboard (1) which is fixed to the wooden support beams (4). In between the wooden beams, insulating material can be placed (3). The exterior wall in figure 5 is constructed out of bricks (7), but the exterior wall could also be made out of other materials, look wooden plating. The air cavity is indicated with number 6 in figure 5. In figure 5 the numbers 2 and 5 are special foils. Foil number 2 stops water vapour, whereas foil number 5 stops liquid water, but not water vapour. This way the wooden construction will not rot.

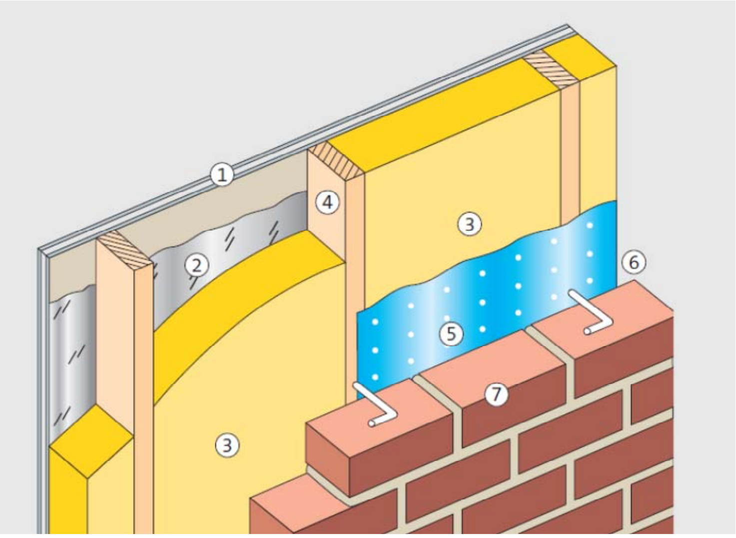
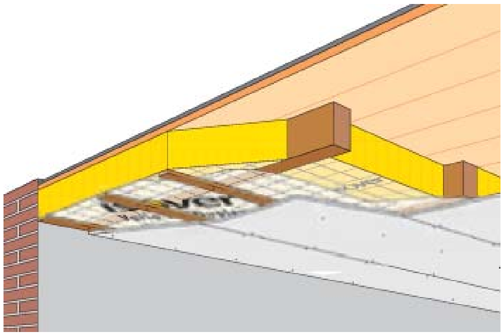


Figure 5, timber frame construction (Isover, 2008)

Roof constructions

- **Flat roof**

Flat roofs are constructed by placing a layer of plating on top of a row of beams which are mounted to two opposite walls. The beams can be made out of wood, steel or concrete. The same goes for the plating. An exception is the case in which thick concrete panels are laid on top of the walls, to create a flat roof in one go. To make the roof watertight, bitumen are used. When the flat roof is insulated this can be done on either side of the roof: insulating materials can be put in between the beams, or insulating material can be put upon the roof and covered with bitumen. Figure 6 and 7 show an example of both the insulating options.



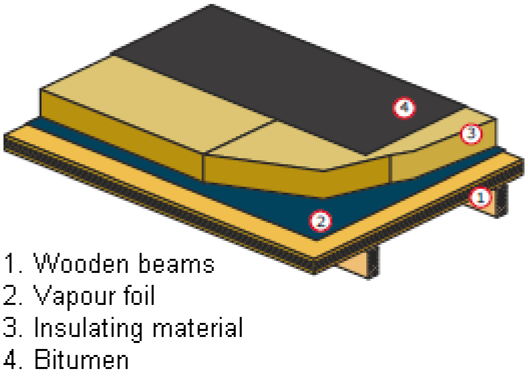


Figure 6, insulation between the beams (Isover, 200X) Figure 7, insulated on top of the roof (Rockwool, 2004)

- **Pitched roof: purlin roof**

There are two commonly used types of pitched roofs: the purlin roof and the rafter roof. Figure 8 shows an example of a purlin roof. The large beams perpendicular with the cullis, are fixed to the brickwork. After the purlins are fixed, wooden plates are mounted on top of them. Upon these plates, tile laths are fixed to support the roof tiles. Before 1975, no insulating material is used. Retrofitting a purlin roof with insulating materials is therefore done by adding insulating material inside the attic.

Figure 8, example of a purlin roof (Adviesbureau Simons, 2009)

When houses are build with a purlin roof nowadays, the basic structure of the wooden beams is still the same. However, prefabricated roof panels exist that contain insulating material and tile laths, so they can easily be mounted on top of the purlins. The roof panels provide both insulation and a base to mount the roof tiles on. Figure 9 shows the mounting of such a roof panel.

Figure 9, mounting of an insulated roof panel with tile laths (NBD, 2010)

- **Pitched roof: Rafter roof**

The rafter roof is constructed out of self supporting wooden beams (rafters). By cutting a small notch into the rafters, they are able to rest on the outer walls of the building. Figure 10 shows how the rafters rest onto the outer walls. In the figure the construction of the ridge can also be seen. By connecting the rafters in the ridge of the roof by either wood or metal plates, a self supporting structure emerges.

Figure 10, construction of a rafter roof (Bouwinfo, 2008a)

Just like the purlin roof, the finished wooden structure (see figure 11) will also be covered in wooden plates on which tile laths are mounted. In buildings build before 1975 that were not subjected to any regulation considering insulation, the roofs are not fitted with insulating materials. When a rafter roof is retrofitted with insulating materials, this is done on the inside of the roof (in the attic), between the rafters.

Figure 11, example of a rafter roof construction (Bouwinfo, 2008b)

When the rafter roof construction is used nowadays, the same type of plates that are placed on top of the purlin roof can be used. This means that the rafter roof can also be finished with prefabricated roof plates which are already fitted with insulating materials (see figure 9).

Floor constructions

- **Wooden floor (wooden beams with wooden flooring)**

A wooden floor is a common type of floor in old houses. Nowadays almost all the newly build houses have concrete flooring. The base of the wooden floor is formed by thick wooden beams that are fixed in the supporting wall on both sides. Upon these wooden beams, flooring can be placed. To prevent the wooden floors from rotting, an empty space is kept underneath the floor. This space is often called the crawl space and contains plumbing and electricity connections. Wooden floors were usually not insulated during construction. Figure 12 shows a schematic view of a wooden floor construction which is retrofitted with insulating materials. These materials must be able to allow water vapour to pass through, to prevent rotting.

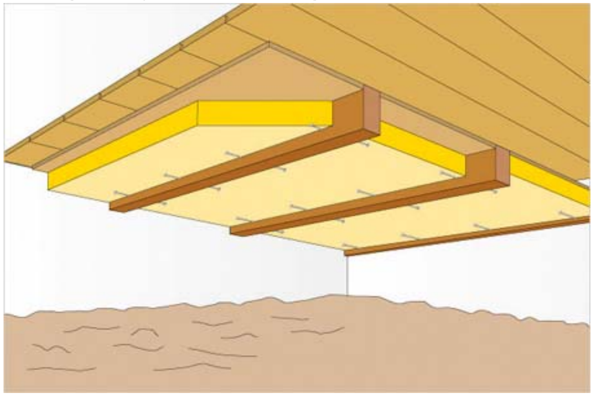


Figure 12, schematic representation of a wooden floor construction (Isover, 2011)

- **Solid concrete floors**

Another way of constructing floors is by using solid concrete floors. These floors can be made at the construction site, but prefabricated floors are also available. Most of the prefabricated floor panels are already equipped with some kind of insulating materials. Polystyrene is the most commonly used materials for insulating concrete floors, since concrete floors are not affected by water vapour or moist. Many of the floors are however equipped with a crawl space. This not space is not needed from an insulation point of view, but it is used for plumbing and electrical wiring. If the floor needs to be retrofitted with insulating materials, this can easily be done by fixing insulating panels underneath the floor, as can be seen in figure 13.

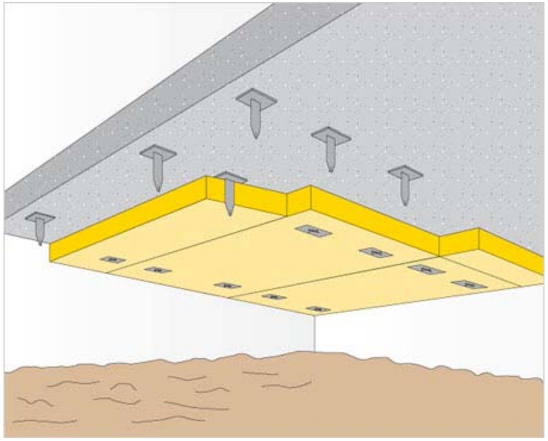


Figure 13, insulating an existing concrete floor

References

Adviesbureau Simons, 2009. *Purlin roof under construction.* [image online] Available at: <http://www.avbsimons.nl/pic/gordingkap.jpg> [Accessed: 14 September 2011]

Bouwinfo, 2008a, *Rafters being mounted to the outer walls*. [image online] Available at: <http://i285.photobucket.com/albums/ll59/bouwforum/Peterfotos180.jpg> [Accessed: 14 September 2011]

Bouwinfo, 2008b. *Rafter roof under construction.* [image online] Available at: <http://www.tuningclubzgzm.be/board/uploads/post-2-1214157633.jpg> [Accessed: 14 September 2011]

Habavo, 2011. *Picture series of renovation project 'de Kroon' in Hoogeveen.* [online] Available at:<http://www.habovo.nl/habovo_afbouw/12/referenties/8/de_kroon_hoogeveen.html> [Accessed: 22 November 2011].

Isover, 2008. *Vademecum voor het isoleren van spouwmuren, vliesgevels en gevelsluitende elementen.* [online] Isover, Vianen. Available at: <http://www.isover.nl/documentatieservice/themabrochures/vademecum/vademecum-voor-spouwmuurconstructies.pdf> [Accessed: 12 September 2011]

Isover, 2011. *Insulating an existing wooden floor.* [image online] Available at: <http://www.kruipruimteisoleren.nl/images/uploads/cms_visual_1598.jpg> [Accessed 14 September 2011>

Isover, 200X. *Renovatie en na-isolatie.* [online] Isover, Vianen. Available at: <http://www.isover.nl/documentatieservice/themabrochures/renovatie-en-na-isolatie/brochure-renovatie-en-na-isolatie.pdf> [Accessed: 14 September 2011]

Jeeninga, H., Volkers, C.H. 2003. *Ontwikkeling van SAWEC. Een Simulatie en Analyse model voor verklaring en voorspelling van het Woninggebonden Energieverbruik en CO2-emissie.* [Online] ECN, Petten. Available at: <http://www.ecn.nl/publicaties/PdfFetch.aspx?nr=ECN-C--03-067> [Accessed 14 September 2011].

Kingspan, 2011a. *Insulation for rainscreen cladding systems.* [online] Available at: <http://www.kingspaninsulation.co.uk/getattachment/1bf975f8-3e5b-476f-9321-3ecf71591931/Kooltherm-K15-Rainscreen-Board.aspx?disposition=attachment> [Accessed 13 September 2011]

Kingspan, 2011b. *Ultiem rendement isolatieplaat voor buitengevelisolatie.* [online] Available at: <http://www.insulation.kingspan.com/nederland/pdf/k5.pdf> [Accessed 13 September 2011]

Kooren, J.A., 200X. *Infoblad 04-02, Thermische isolatie van baksteen gevelconstructies.* [online] KNB, Velp. Available at: <http://www.betrouwbaarbaksteen.nl/images1/betrouwbaarbaksteen/bestanden/04-02%20Isoleren%20steenconstructies.pdf> [Accessed 12 September 2011]

Kuindersma, P., 2010. Bouwdetails deel 12: gevelisolatie met gepleisterde afwerking, *Bouwen nu,* [online] Available at: <http://www.kevindebresser.nl/Publicatie%20Bouwen%20Nu.pdf> [Accessed 14 September 2011]

Nederlandse Bouwdocumentatie (NBD), 2010. *Mounting of prefabricated roof panels.* [image online] Available at: <http://static.nbd-online.nl/pictures/3568-L-03-5.jpg> [Accessed: 14 September 2011]

Rockwool, 2004. *Renovatiebrochure.* [online] Rockwool, Roermond. Available at: <http://www.rockwool.nl/files/RW-BNL/documents/pdf/NL/brochures/Renovatie.pdf> [Accessed 14 September 2011]

Sto Isoned, 2011. *Brochures on product and systems for wet render systems*. [online] Available at: <http://www.sto.nl/86448_NL-Downloads-Brochures.htm> [Accessed: 21 November 2011].

B. Overview of insulating materials

Table of Contents

1 Technical aspects of insulating materials

For a material to be considered an insulating material, it must hold certain properties. This section is aimed at finding the technical aspects that are important for insulating materials.

1.1 Thermal conductivity

The main reason for using insulating materials is the reduction of heat losses from the inside of a building to the outside. The barrier that stands in between the inside and outside is the so called building envelope of a building. To accomplish a reduction in heat loss, the thermal resistance of the building envelope must high. Insulating materials are used in order to reach a high thermal resistance. How well an insulating material resists heat, is determined by the material's thermal conductivity (λ) in W/m·K. Thermal conductivity can be seen as a measure of the effectiveness of a material in conducting heat. The thermal conductivity of a material is needed in order to calculate the heat flow through a piece of material, as equation 1 shows (Blok, 2009):

$$Q = \lambda \cdot \frac{\Delta \mathrm{T}}{d} \cdot A = k \cdot \Delta T \cdot A$$

equation 1.1 heat flow through a material

In which:
Q = heat flow [W]
ΔT = Temperature difference across the material [K]
d = Thickness of the material [m]
A = Surface of the material [m^2]
λ = Thermal conductivity of the material [W/m·K]
k = Heat transmission coefficient (λ/d) [$W/m^2 \cdot K$]

Thermal resistance

From equation 1.1 it is clear that the lower the thermal conductivity of a material is, the lower the heat flow and therefore the heat loss will be. For insulating materials, the thermal conductivity therefore is an important aspect. In equation 1.1, the heat transmission coefficient *k* is used. When this *k-value* is inverted, the thermal resistance for a particular material thickness is obtained (Blok, 2009).

The way thermal insulating materials resist heat flow depends on microscopic cells in which air or other gasses are trapped and therefore still. Because the air or gas within the cells is still (prevented from moving) convective heat transfer is suppressed. The insulating material itself is therefore not the provider of thermal resistance, but the air or gas trapped inside the material. The theoretical thermal resistance limit of insulating materials is set by the thermal resistance of the still air or gas used within the material (Al-Homoud, 2005). The type of gas used within the material is therefore an important aspect of the material, since it influences the thermal conductivity and hence the thermal resistance. In table 1.1 the thermal conductivity of different gases used for insulating materials is given. Another option is to not use a gas at all, but to work with (near) vacuums.

table 1.1 Thermal conductivity of gases used for insulating materials

Gas	λ [W/m·K], T=200K	λ [W/m·K], T=300K
Air	0.0184	0.0262
CO_2	0.0096	0.0168
Pentane	-	0.0144

Declared thermal conductivity
From table 1.1 it is clear that the thermal conductivity of a gas changes with its temperature. The determination of a materials thermal conductivity must be done uniformly, so that a fair comparison between the materials can be made. In NEN-1068:2001 the way of determining the thermal conductivity of insulating materials is prescribed.

Determining the declared thermal conductivity (λ_D) starts with a series of tests in which the thermal conductivity of a material is measured. A minimum of ten measurements is needed with an accuracy of three significant figures at a temperature of 10°C. From these measurements, the $\lambda_{90/90}$ is calculated. This is the statistically determined value of the thermal conductivity which represents 90% of the production with a reliability of 90%. It is calculated by equation 1.3

$$\lambda_{90/90} = \lambda_{average} + k \cdot s_{\lambda}$$

equation 1.3 calculation of $\lambda_{90/90}$

$$s_{\lambda} = \sqrt{\frac{\sum_{i=1}^{n} (\lambda_i - \lambda_{mean})^2}{n-1}}$$

equation 1.2 spreading of measured values

In which:

λ_{mean} = mathematical average of the measured values
k = factor depending on the number of values (e.g. n=10, k= 2.07; n=20, k=1.77)
n = number of measured values
s_λ = standard deviation, calculated according to equation 1.2
λ_i = value of measurement *i*

From the calculated $\lambda_{90/90}$ value, the λ_D is obtained by rounding the $\lambda_{90/90}$ to the closest 0.001W/m·K (NEN 1068, 2001)[1]. Since all producers of insulating materials are obliged to use these norms, the thermal conductivities are measured and calculated in the same way and can therefore be compared to each other.

Density
Another factor that is of influence on the thermal conductivity of a material is the density of a material. A lower density means that there is less material which can conduct heat and there is more air or gas to resist the heat. However, for certain purposes like flat roofs or cavity walls, self supporting materials or materials with a high compressive strength are needed. This can only be achieved by a more dense structure of the materials. A denser structure results in a higher thermal conductivity.

1.2 Fire classification

Thermal insulating materials must have a fire classification. This classification is important because it can be of influence on the application of insulating materials. A fire classification is part of the CE-marking that all construction materials are obliged to have (Bouwbesluit, 2003a). The classification is prescribed in the European norm EN-13501-1. In the norm, seven main classes are specified: A1, A2, B, C, D, E and F, in which A1 is non-flammable and E is highly flammable. If a product has no specification, or is extremely flammable, it will receive class F. Besides the main classes, there are two other classes: smoke growth rate (s1, s2 or s3) and flaming droplets or particles (d0, d1 or d2) (NEN-13501-1, 2009). During this research, only the main classes will be reported (A1, A2, B etc.), because the latter two classes are more product specific than material specific. Next to that, it is the

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[1] Note that for some materials, the aging of the materials (the leakage of gas from gas cells within the material) needs to taken into account. For these materials (e.g., XPS, PUR, PF) this process is prescribed in NEN-EN 13164 to NEN-EN 13166 respectively.

entire construction that is assessed for its fire class, not the separate materials. Materials with a low fire class of for instance E or F, can still be used within a construction, as long as the required classification for the entire construction is reached. However, although the requirements differ per construction and residential function, the lowest classification is D, with smoke class s2. For flaming droplets, there is no requirement in the Dutch building decree (Staatscourant, 2005).

1.3 Moisture

When the building envelope of a building is insulated, attention must be paid towards the prevention of moisture problems. These problems are the result of condensing water vapour and can lead to structural damage (rotting of wood) or wet spots that form a breeding place for mould. If warm air with a high humidity diffuses from the inside of a building to the colder outside, the water vapour could condense within the insulating material. This diffusion of warm water vapour to the less humid outside environment occurs because of a difference in vapour pressure. The vapour pressure inside the building is higher than the vapour pressure outside. By the diffusion of water vapour from the high to the low pressure, this unbalance is cancelled out. The high humidity inside buildings is due to the users of the building: cooking, showering, plants and the water vapour exhaled by humans, contribute to an increasing humidity. (Van den Hout et al, 2005).

Water vapour diffusion resistance

To determine the vapour permeability of a material, equation 1.4 is needed to determine the water vapour resistance of a material.

$$Z = \frac{\mu \cdot d}{\delta_{air}}$$

equation 1.4 water vapour diffusion resistance

In which:
Z = water vapour diffusion resistance [m/s]
μ = Water vapour diffusion resistance factor [-]
d = thickness of the material
δ_{air} = Water vapour conduction coefficient of air ($0.185 \cdot 10^{-9}$)

When the water vapour diffusion resistance of an entire construction (e.g. wall, floor, roof) has to be determined, the resistances of the individual materials can be added up. This leads to the expression as given in equation 1.5.

$$\sum Z = 5.4 \cdot 10^{9} \cdot \sum \mu \cdot d$$

equation 1.5 summation of resistances

From equation 1.5 it is clear that if the water vapour diffusion resistance factor (μ) of a material is known, the total water vapour diffusion resistance (Z) can easily be calculated. This Z-value can be used for the calculation of the water vapour pressure change over the entire wall, roof or floor construction. With this change in water vapour pressure, areas can be identified at which condensation could occur and prevented if necessary (Van den Hout et al, 2005 & Hasselaar, 2004).

Water vapour diffusion resistance factor (μ)

The μ value of an insulating material gives the relation between how much water vapour diffuses through a layer of air, and a layer of material of the same thickness:

$$\mu = \frac{\text{vapour diffusion resistance of a material with thickness d}}{\text{vapour diffusion resistance of an air layer with thickness d}}$$

μ is therefore a useful indicator for insulating materials, because it gives a good first impression of a materials vapour diffusion resistance, which can be of influence on the practical application.When building a vapour closed construction, it is useful to use materials with a high μ. The μ value for materials is greater than or equal to one (Hasselaar, 2004).

Next to insulating materials, there are also materials that are used because of their high µ-value. PE-foil for instance has a µ value of 50,000 and is therefore often used as a vapour barrier to prevent water vapour from inside the house to enter the insulating material. This is usually done during the renovation of pitched roofs with mineral wools, for these materials have a low µ (1-2) (Isover, 2008).

1.4 Price

For the determination of the prices, the price of insulating a cavity wall to a certain thermal resistance will be determined. This is done per material, so that insight is provided in both the practical applications as the costs.

Cavity wall

To calculate the price of the materials, the thickness of the needed material must be determined. This calculation is done according to the Dutch practical directive NPR 2068:2002. In this directive, the legal method of calculation a cavity wall's thermal resistance ($R_{construction}$) is prescribed. This prescription is in accordance with the requirements of the 2003 building decree which requires cavity walls to have a R_c of at least 2.5 $m^2 \cdot K/W$ (Bouwbesluit, 2003b). In 2012, a new version of the building decree will come into force, in which the standard is raised to 3.5 $m^2 \cdot K/W$ (Concept Bouwbesluit, 2011).

The calculation is best explained by using a sample cavity wall from NPR 2068. A cross-section of this cavity wall is depicted in figure 1.4.1. The wall is constructed out of 100mm of brickwork on the outside (1), a 40mm air cavity (2), a 100mm thick layer of insulating material (3) and a 100mm sand-lime brick inner wall (4).

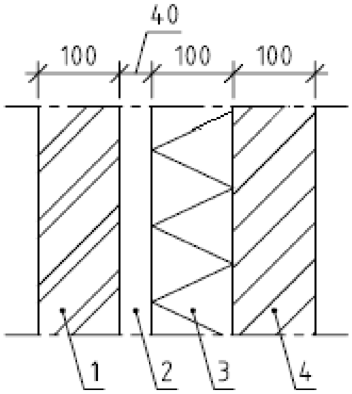

figure 1.4.1 cavity wall from NPR 2068:2002

With the four elements of the cavity wall from figure 1.4.1, its R_c can be calculated with equation 1.6.

$$R_c = \frac{\sum R_m + R_{si} + R_{se}}{1+\alpha} - (R_{si} + R_{se})$$

equation 1.6 calculation of R_c-value

In which:
R_c = Thermal resistance of the entire cavity wall construction [$m^2 \cdot K/W$]
R_m = Thermal resistance of the different materials [$m^2 \cdot K/W$]
R_{si} = Heat transition resistance of the incoming heat flow [$m^2 \cdot K/W$]
R_{se} = Heat transition resistance of the exiting heat flow [$m^2 \cdot K/W$]
α = Correction factor for the existence of internal convection and construction influences [-]
When cavity wall is constructed on the building site, the value for α is 0.05. For prefabricated elements, α becomes 0.02. If cellular glass is used, α becomes 0.

The thermal resistance of the different materials (R_m) is calculated by dividing the thickness of the material by its 'calculation' thermal conductivity (λ_R). This calculation thermal conductivity is derived from the declared thermal conductivity (λ_D) by using equation 1.7.

$$\lambda_{calculation} = \lambda_{declared} \cdot F_T \cdot F_m \cdot F_A$$

equation 1.7 determination of λ_c

In which:
F_t = 1.0 if the annual temperature is between 5 and 20˚C, which for the Netherlands is true.
F_m = A factor to correct for the influence of moisture in certain situations, like inverted roofs. For cavity walls and pitched roofs, this value is 1.
F_A = A correction factor for the aging of in-situ materials, like blown in foams or flocks. For Factory made insulating materials the value 1 is used.
From the factors needed for equation 1.7 it can be concluded that in most cases $\lambda_{calculation} = \lambda_{declared}$.

For the price calculation, the R_c that needs to be reached is 3.5 $m^2 \cdot K/W$. According to the directive, the R_m for the inner sand-lime brick wall, air cavity and brickwork are 0.10, 0.18 and 0.10 $m^2 \cdot K/W$ respectively. The values needed for R_{si} and R_{se} are provided in NEN 1068:2001 and are 0.13 and 0.04 $m^2 \cdot K/W$ respectively. The only unknown value now is the thermal resistance of the insulating material (R_{IM}).By rewriting equation 1.6, an equation is obtained from which R_{IM} can be calculated:

$$R_{IM} = -(\sum R_{cavity\,wall\,elements} + R_{si} + R_{se}) + [(1+\alpha) \cdot (R_c + R_{si} + R_{se})]$$

$$R_{IM} = -(0.38 + 0.13 + 0.04) + [1.05 \cdot (3.5 + 0.13 + 0.04)] = 3.3035 \ [m^2 \cdot K/W]$$

equation 1.8 thermal resistance of insulating material in cavity wall

Since R_{IM} is calculated by R_{IM}=thickness of insulating material / λ, its thickness can be calculated by filling in the λ values of different insulating materials. With this thickness, a matching product consisting of a specific material can be sought-after, from which the price can be determined. However, the insulating materials are fixed by fasteners that stick through the material. These fasteners influence the thermal conductivity of the material. Therefore, the influence of the fasteners is taken into account by calculating a composed thermal conductivity according to equation 1.9.

$$\lambda_{composed} = \frac{(\lambda_{calculation} \cdot A_{IM} + \lambda_{fasteners} \cdot A_{fasteners})}{(A_{IM} + A_{fasteners})}$$

equation 1.9 composed thermal conductivity

In which:
$\lambda_{composed}$ = Composed thermal conductivity [W/m·K]
$\lambda_{fasteners}$ = Thermal conductivity of the fasteners [W/m·K]
A_{IM} = Net surface of the insulating material [m^2]
$A_{fasteners}$ = Surface of used fasteners [m^2]

For $A_{fasteners}$ and $\lambda_{fasteners}$ value from NPR 2068:2002 are used. This means stainless steel fasteners with a diameter of 4mm and a thermal conductivity of 15W/m·K. The number of fasteners per m^2 depends on the width of the cavity. In table 1.2 the number of fasteners per m^2 according to Rentier et al. (2005) is given. When the cavity gets wider, this also has an effect on the thickness or material of the inner wall. A cavity wall with a cavity wider than 150mm must have an inner wall made of brickwork over 100mm thick, or has to be constructed out of concrete. The minimal thickness for a concrete inner wall is 150mm according to Spierings et al. (2004). Producers of insulating materials consider 160mm to be a commonly used thickness. 160mm is therefore the value used in calculations, when the cavity exceeds 150mm. Calculation for a cavity smaller than 150mm, a 100mm sand-lime brick wall is assumed. With a λ value for concrete of 2W/m·K according to NPR 2068:2002, the R_m value for a concrete inner wall becomes 0.08 $m^2 \cdot K/W$.

table 1.2 influence of cavity width on fasteners and inner wall construction (Rentier et al, 2005)

Cavity width [mm]	Fasteners [n/m^2]	Diameter fasteners [mm]	Inner wall construction
50-150	4	4	At least 100mm brickwork
150-300	6	4	concrete or >100mm brickwork
150-300	4	5	concrete or >100mm brickwork

2 Categories of insulating materials

To compare the insulating materials, a division is made by setting up material categories. According to Papadopoulus (2005) four categories can be defined that are based on the chemical composition of the base material from which the insulating material is produced. These four main categories are:

1. Inorganic materials
2. Organic materials
3. Combined materials
4. New technology materials

For this research, the third category 'combined materials' is not used, because it lists insulating materials that consist out of multiple materials (e.g. foam with plasterboard). Since the focus lies on commonly used and new insulating materials, the fourth category is used together with category one and two from the above list. This allows both new (high tech) and commonly used materials to be divided into categories easily.

The three categories that remain are still very general and should be more detailed. To do so, the organic materials are split into two groups: materials made from a petrochemical base (e.g. polymers like polystyrene, polyisocyanurate) and materials made from renewable resources (e.g. sheep's wool, flax). This separation is useful, because the renewable materials are not common materials yet, but might become so. The inorganic insulating materials have a mineral base material (cullet or basalt for example) (VIBE, 2007). Another division that can be made according to Papadopoulus is the structure of the materials (e.g. foamy, fibrous). This division does not cover all materials. Calcium Silicate for instance, is a material that is inorganic, not fibrous, but also not foamy. Therefore the category 'cellular' is used (Al-Homoud, 2005). Since the structure of the material could be of influence on its practical application, this division is made as well. Figure 1 shows the classification scheme that is derived from both Papadopoulos and Al-Homoud. No fibrous petrochemical materials were encountered during the search for materials, therefore the category 'fibrous' is left out.

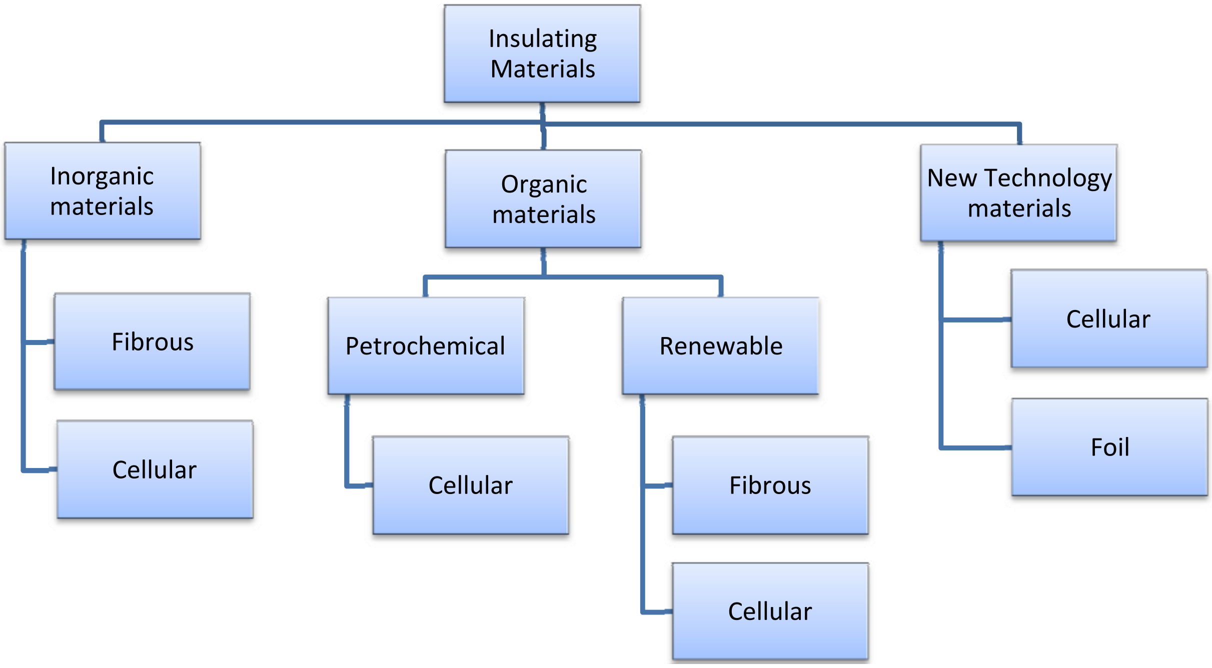

figure 2.1 categorization of insulating materials

Categorizing the insulating materials allows a conveniently arranged overview to be created. In the following chapter the different categories will be filled with materials, starting with the inorganic materials from figure 2.1.

3 Inorganic insulating materials

According to Papadopoulus, Al-Homoud, VIBE and Jelle (2011) the following inorganic insulating materials are used for building insulation and are classified accordingly:

- Fibrous
    - Glass wool
    - Rock wool
- Cellular
    - Calcium silicate
    - Cellular glass
    - Perlite & Vermiculite

3.1 Inorganic: fibrous

Glass- and rock wool are produced from mineral fibres and are therefore often referred to as ‘mineral wools’. Mineral wool is therefore a generic term and not itself a material. Glass- and rock wool are the most common type of insulating material used today. The combined European market share of glass- and rock wool is around 60% (Pappadopoulus, 2005).

3.1.1 Glass wool

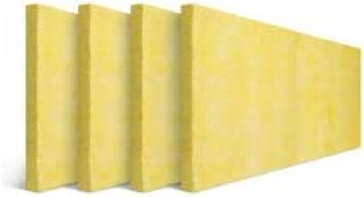

figure 3.1.1 glass wool panels (Isover, 2010)

Production

For the production of glass wool borosilicate glass (quartz sand), recycled glass (cullet) and additives (fluxing agents like dolomite) are needed (Isover, 2009, Jelle, 2011). These base materials are melted in a furnace at around 1450°C. From the melted materials, fibres are spun. This process is comparable with the spinning of candy floss, in which sugar is melted and spun into fibres. During the spinning of the glass fibres, a binding agent is injected. As a binding agent, phenol-formaldehyde-urea resin is commonly used (Kowatsch, 2010). After the glass fibres are spun, they are shaped into form and send through a curing oven, where the added binding agents give the glass wool its distinctive yellow colour.

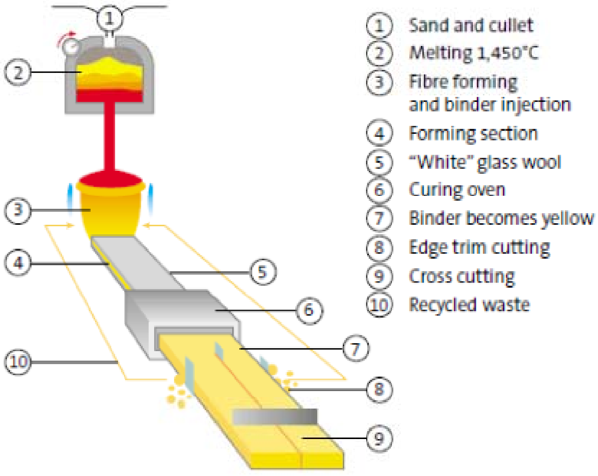

figure 3.1.2 production of glass wool (Isover, 2009)

After the curing oven, the glass wool batt is cut into shape. Glass wool comes in the shape of panels (figure 3.1.1), rolls and flocks. In figure 3.1.2, the production process of glass wool is depicted schematically.

Thermal conductivity and density

The thermal conductivity (λ_D) of glass wool lies between 0.030 and 0.040 W/m·K (Jelle, 2011). Two large producers of glass wool, Knauf and Isover, also present λ_D values for their products that fall within this range. Since glass wool consists largely of air, its density is between 12-150 kg/m^3 (Kowatsch, 2010). The varying in the density depends on the purpose of the glass wool. When compressed into panels, the density goes up in order to reach a higher compressive strength, or to make the panels self supporting.

Fire class

Fire class: A1 and therefore no production of smoke or flaming droplets. However, glass wool products (panels, rolls) can be layered with materials for either comfort, moisture or extra insulation that can lower the fire class.

Water vapour resistance factor

$\mu \geq 1$

Practical application

Glass wool can be used for the insulation of both walls, floors and roofs. It is an all-round material that can be used in almost every type of building envelope construction. Due to alterations of the different products, a glass wool product is available for almost every purpose. In all of these products glass wool is the ‘working’ material.

Price

For the insulation of the cavity from section 1.4, many glass wool products are available. A large producer of glass wool products is Isover. One of their products suitable for cavity walls is ‘Mupan’. Mupan consists of glass wool panels, that come various designs. The most simple design is just a glass wool panel with a glass film on both sides. This product has a λ_D of 0.035 W/m·K.
When the calculation according to section 1.4 is performed, the needed thickness of the material is 118mm. Mupan is available in panels of 120mm thick. The price of these panels is €9.30/m^2. (Isover, 2011). Two other Mupan designs are available as well: ‘Mupan plus’ with a λ_D of 0.033W/m·K and ‘Mupan Ultra XS’, which has a reflective foil one side and a λ_D of 0.028W/m·K.

Another producer of glass wool products is Knauf. Their products are quite similar to the products from Isover mentioned earlier. To make a fair comparison, these similar products are taken into account as well. In order to reach R_c = 3.5 m^2·K/W this gives the options as listed in table 3.1.

table 3.1 glass wool product prices to reach R_c=3.5. All prices are without VAT (Knauf, 2011 & Isover, 2011).

Product	Producer	λ_D [W/m·K]	Thickness [mm]	Price [€/m^2]
Mupan	Isover	0.035	120	9.30
Mupan Plus	Isover	0.033	115	11.75
Mupan Ultra XS	Isover	0.028	97	13.30
Cavitec 036	Knauf	0.036	125	9.60
Cavitec 035	Knauf	0.035	120	11.10
Cavitec 032 premium	Knauf	0.029	100	14.70
Cavity wool (flocks)	Isover	0.045	149	15.76

3.1.2 Rock wool

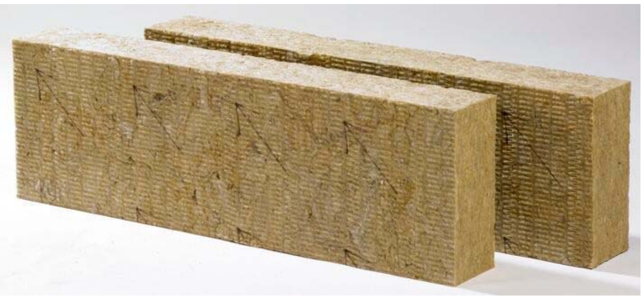

figure 3.1.3 rock wool panels (Passiefhuismarkt, 2011)

Production
Rock wool is produced from two minerals: diabase (dolerite) or basalt. Next to virgin materials, also recycled rock wool can be added to the process as well as slag residues from the metal industry. When only this slag forms the base material, the obtained product is called slag wool. The production process of rock wool is similar to the glass wool production. The base minerals are melted inside a cupola oven at around 1500°C. Cokes are used as fuel for the cupola oven (Jelle, 2011). As in the production of glass wool, dolomite (limestone) is added as a fluxing agent (Kowatsch, 2010). From the molten minerals fibres are spun, by pouring the molten material onto spinning disks through which air is blown. The spun fibres are bonded with a binding agent, to create flocks, panels (figure 3.1.3) or rolls. For the binding process phenol-formaldehyde-urea resins are used (Kowatsch, 2010).

Thermal conductivity and density
According to Jelle (2011), typical thermal conductivity values for mineral wools are between 0.030 and 0.040W/m·K. Both Rockwool and Knauf, two large rock wool producers, produce their rock wool with a thermal conductivity of 0.035W/m·K, which is right in between the 0.030 and 0.040W/m·K The density values of rock wool are between 25 and 200 kg/m^3 (Al-Homoud, 2005; IBU, 2008). A higher density occurs when the rock wool is pressed into panels that need a higher compressive strength.

Fire class
Rockwool has fire class: A1 (non-flammable) and therefore does not produce any smoke or flaming droplets. Like glass wool, products (panels, rolls) can be layered with materials for either comfort, moisture or extra insulation that can lower the fire class.

Water vapour diffusion factor
μ = 1 to 5.

Practical application
Rock wool is a versatile material that can be used for the insulation of walls, roofs and floors. For virtually all the types of constructing a building envelope, a rock wool product can be used as insulating material. During the installation of the rock wool, it should be kept dry at all times. Although rock wool is treated against moisture, the thermal conductivity will get significantly lower when it gets wet. A increase of the moisture content from 0vol% to 10vol% causes a thermal conductivity increase from 0.037W/m·K to 0.055W/m·K respectively (Jelle, 2011). This also applies to glass wool. Mineral wools should therefore be kept dry at all times.

Price
Mineral wool can be applied in cavity walls. Therefore the calculation from section 1.4 is used to determine prices for Rockwool products in order to reach an of R_c=3.5. For the determination of the prices, the price catalogue of Rockwool (a large producer) is used. Rockwool provides four products for the insulation of cavity wall (all panels). The simplest design is the “Spouwplaat 433 Mono” with a λ_D of 0.035 W/m·K. The most advanced product is a panel that is lined with a reflective foil on one side with a λ_D of 0.029 W/m·K. With the calculation method of section 1.4 and the Rockwool price

catalogue, prices for insulating to R_c=3.5 are obtained. Just like with glass wool, another producer of rock wool is taken into account. Because Knauf also produces Rockwool, their product prices are used as well. The total result can be found in table 3.2. The Knauf products from the table are rock wool panels without any reflective foil.

table 3.2 rock wool product prices to reach R_c=3.5. All prices without VAT (Rockwool, 2011 & Knauf, 2011)

Product	Producer	λ_D [W/m·K]	Thickness [mm]	Price [€/m^2]
SpouwPlaat 433 Mono	Rockwool	0.035	120	12.25
SpouwPlaat 433 Plus	Rockwool	0.033	115	15.80
SpouwPlaat 433 HP	Rockwool	0.029	100	17.95
Cavity Slab	Knauf	0.035	120	12.30
Cavity Slab HD	Knauf	0.034	120	20.05

3.2 Inorganic: cellular

3.2.1 Foam glass (cellular glass)

figure 3.2.1 foam glass panel (Foamglas, 2011)

Production

In figure 3.2.2 the production process of foam glass is depicted. To produce foam glass, a mixture of recycled glass, feldspar, dolomite and other additives are used to create glass with the desired properties for foam glass at a temperature of 1250°C. The produced glass is cooled down and milled. Carbon is added during the milling of the glass. This mixture of carbon and milled glass is poured into moulds. The filled moulds pass through the foaming furnace (8 in figure 3.2.2). In the foaming furnace the temperature is around 850°C, causing the carbon to oxidise, creating CO_2. The CO_2 is trapped in the glass, creating a cell structure (hence, cellular glass). After expanding, the foam glass is annealed and taken out of the mould. The newly produced foam glass blocks get trimmed and cut into shape, after which they are ready to use (Foamglas, 2011). A trimmed and cut panel is shown in figure 3.2.1.

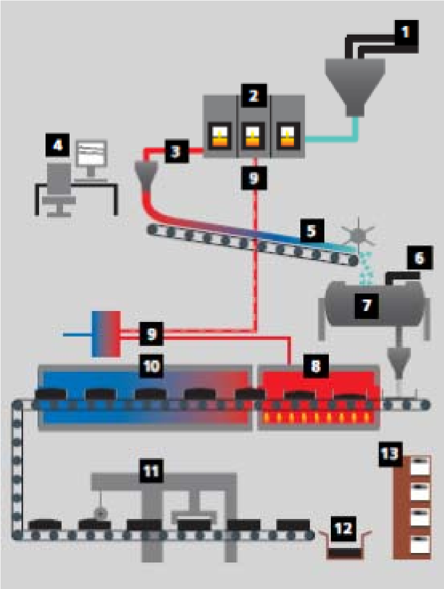

figure 3.2.2 foam glass production process (Foamglas, 2011)

Thermal conductivity and density

Foam glass has a thermal conductivity ranging from 0.038 to 0.055W/m·K. The thermal conductivity depends of the density of the foam glass, which ranges from 100kg/m^3 to 200kg/m^3 (Foamglas, 2007).

Fire class

Because foam glass is entirely made of inorganic materials it has fire class A1 (non-flammable).

Water vapour resistance factor

The dense cell structure is complete made out of glass, giving the material an infinite μ, no water vapour can pass through the material.

Practical application

Due to the fact that foam glass is made of expanded glass, it has a high compressive strength, up to $3N/mm^2$. This makes the material very suitable for the insulation of flat roofs which are covered with bitumen of other heavy substances. Next to insulating of roofs, foam glass can also be used for the insulation of walls on both the in- and outside. Because foam glass is a vapour barrier, it is not suitable for the insulation of pitched roofs and wooden flooring, therefore making it less suitable for renovation.

Price

To calculate the price for the insulation of a cavity wall with foam glass according to section 1.4, the price is based on products made by Foamglas. The only products suitable for cavity wall insulation is Foamglas Wall Board T4+ (λ_D = 0.041W/m·K) and Foamglas W+F (λ_D = 0.038 W/m·K). With the thermal conductivity values the thickness of products can be determined to reach R_c = 3.5. For Foamglas Wall Board T4+, this gives 138mm and for Foamglas W+F this gives 129mm. The accompanying product thickness and prices are presented in table 3.3.

table 3.3 foam glass product prices to reach R_c=3.5. All prices exl. VAT (Foamglas, 2010)

Product	Producer	λ_D [W/m·K]	Thickness [mm]	Price [€/m^2]
Wall Board T4+	Foamglas	0.041	140	62.37
Foamglas W+F	Foamglas	0.038	130	46.46

3.2.2 Calcium Silicate

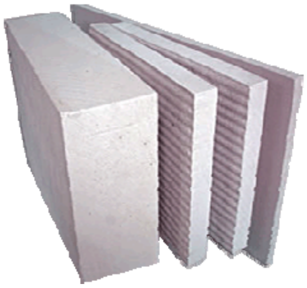

figure 3.2.3 Calcium silicate panels (Kuhnen, 2011)

Production

By mixing chalk, pure sand, water and additives together a predecessor of the desired calcium silicate is produced. The mixture is shaped into panels (see figure 3.2.3) that are placed in an autoclave (see figure 3.2.4). Due to the high pressure and steam in the autoclave, the calcium silicate crystals form a porous open structure that gives the panels their insulating properties. To provide extra strength, cellulose fibres (up to 10%) can be added to the mixture before it enters the autoclave(Calsitherm, 2010).

figure 3.2.4 Calcium silicate panel autoclave (Calsitherm, 2010)

Thermal conductivity and density

The thermal conductivity of calcium silicate panels is between 0.059 and 0.065W/m·K when the panels have a density between 200 to 240kg/m^3.

Fire class

Calcium silicate has fire class A1 (non-flammable).

Water vapour resistance factor

μ = 6- 20

Practical application

Calcium silicate can only be used for the insulating of the building envelope from the inside. The panels need to be glued to the inside of the exterior wall, after which they can be finished with for instance a render. Because the compressive strength of calcium silicate panels can be around 2.8N/mm^2 it can also be used for blocking cold bridges. However, with an increase of the compressive strength, the density increases as well. This density increase causes an increase in the thermal conductivity. Calcium silicate panels are porous and therefore soft. This means that whenever something needs to mounted to the wall (e.g. pictures, sinks, bookshelves), special plugs or wall mounts are needed.

Price

Since calcium silicate can only be used as an insulating material indoors, it cannot be used within a cavity wall. Besides that, the relatively high thermal conductivity of calcium silicate would result in very thick layers (198mm for λ=0.059 and 218mm for λ=0.065W/m·K).

3.2.3 Vermiculite & Perlite

Vermiculite and perlite are treated together, because the materials are quite similar. The ore of both the materials gets crushed into granules, after which it is heated to expand the granules. The structure of perlite and vermiculite are different, as can be seen in figure 3.2.5. Vermiculite has a layered structure, whereas perlite has a non crystallized structure of cells in which water is bound.

figure 3.2.5 left: exfoliated vermiculite right: expanding perlite (NVM, 2004 & Reppel, 2005)

Production

Vermiculite is a magnesium-aluminium silicate which is capable of expending at high temperatures (900°C). The vermiculite ore has a layered structure in which water is bound. When the vermiculite is heated, water vapour is set free and exfoliates the layered structure, leaving air cavities in the vermiculite structure (Bouwcenter, 2007).

Depending on the raw material producing area, perlite consist for 65-80% out of silicon dioxide, 2-6% water and other minerals. (Bouwcenter, 2007). Just like vermiculite, perlite is heated to a temperature of about 900°C. At this temperature, the water vapour expands the perlite, leaving air cavities within the material. The expanding of perlite is best compared to popping popcorn, only then at much higher temperatures.

Thermal conductivity and density

Perlite has a thermal conductivity between 0.040 and 0.060 W/m·K and can have a density varying between 32 and 176kg/m^3. Vermiculite has a thermal conductivity ranging from 0.040 to 0.068W/m·K and a density between 64 and 130kg/m^3 (Reppel, 2005 & Al Homoud, 2005). The lowest thermal conductivity value is for the pure vermiculite and pure perlite.

Fire class

Both perlite and vermiculite have fire class A1, independent of their form (panels or granules).

Water vapour resistance factor

For both perlite and vermiculite: μ = 3-5.

Practical application

Both perlite and vermiculite are used to create insulating panels. To create such panels, fibres (cellulose) and binding agents (starch) are added to the granules and pressed into panels. Panels have a lower thermal conductivity than the loose granules: 0.051W/m·K. These panels are mostly used for the insulation of flat roofs which are finished with bitumen (VIBE, 2007 & Johns Manville, 2010).

Next to panels, the vermiculite and perlite granules can also be added to concrete- and render mortars, to create insulating floors and walls (albeit more for acoustic purposes). When the perlite granules are impregnated with silicon, they can also be used within cavity walls for both new and renovated buildings. The granules can also be impregnated with bitumen, to make them suitable for levelling floors. The thermal conductivity of the impregnated granules is around 0.045W/m·K

(Reppel, 2008). Vermiculite granules cannot be used to insulate cavity walls, because the granules take up moisture.

Price

Since both perlite and vermiculite panels are not used to insulate cavity walls, calculation along section 1.4 cannot be done. However, perlite granules can be used to insulate cavity walls. The granules used in cavity walls must be treated with silicon, to make them waterproof. The products from Knauf are perlite granules impregnated with silicon, so that they are waterproof. The Hyperlite granules can be used in new cavity walls, whereas the Hyperdämm granules can be blown into existing cavity walls. The price of both products is the same, but due to the lower λ of Hyperdämm, the price per m^2 is lower. Because the material is placed 'in-situ' the λ_D has to be multiplied with 1.2, according to NEN 1068:2001 to obtain the correct $\lambda_{calculate}$. The number of fasteners between the inner and outer wall changes. This is because the width of the cavity becomes larger than 150mm, so 6 fasteners are now needed with a concrete inner wall. This gives a $\lambda_{composed}$ of 0.055 W/m·K for Hyperdämm and 0.061W/m·K for Hyperlite. With these values, the needed thickness the perlite granules can be calculated according to section 1.4. The results are presented in table 3.4.

table 3.4 prices (exl VAT) of vermiculite and perlite granules based on VIBE (2007) and NaturBauHof (2011) to reach R_c=3.5

Product	Producer	λ_D [W/m·K]	Thickness [mm]	Price [€/m^2]
Hyperlite-KD	Knauf	0.050	204	42.41
Hyperdämm	Knauf	0.045	184	38.25

4 Organic insulating materials: petrochemical

The organic insulating materials treated in this section are all derived from a petrochemical feedstock and almost all of the materials are therefore polymers. For the petrochemical materials the categorization is unambiguous: cellular. A material is cellular when the structure of the material consists of pores or cells. This results in the following list of materials (VIBE, 2007, Bouwcenter, 2007, Papadopoulus, 2005, Jelle, 2011):

- **Cellular**
    - Expanded polystyrene (EPS)
    - Extruded polystyrene (XPS)
    - Polyurethane (PUR)
    - Polyisocyanurate (PIR)
    - Urea formaldehyde (UF)
    - Phenol formaldehyde (PF)

4.1 Cellular

4.1.1 Expanded polystyrene (EPS)

figure 4.1.1 EPS panels (Betonson, 2011)

Production

EPS is produced from the monomer 'monostyrene', which is derived from benzene and ethylene, both petroleum products. By polymerizing the monostyrene with a blowing agent (pentane) and hexabromocyclododecane (HBCD, a flame retardant), polystyrene beads are formed. These beads are also referred to as polystyrene granulate. In the next step of the process, the beads are heated with steam, causing the pentane to expand the granulate which is softened by the heat from the steam. Within the granulate, a cell structure is created in which air has replaced pentane. After the granulates are expanded they are called 'pearls'. These pearls are blown into silos, where are cooled down and stored until further process. To produce panels from the loose pearls, they are heated once more and pressed into panels. Because of the heat and pressure, the pearls melt together into the desired shape. The used pentane in the EPS is replaced by air. The EPS pearls are therefore only filled with air. The flame retardant HBCD can be chemically bonded within the polystyrene during the polymerization process, or physically bonded during the production of EPS products. (Kemisol, 2004 & Stybenex, 2007).

Thermal conductivity and density

The density of polystyrene can vary from 10 to 80kg/m^3 and the thermal conductivity ranges from 0.032 to 0.045 W/m·K (Kemisol, 2004).

Fire class

When EPS is treated with a flame retardant the fire class becomes E (untreated: F). When EPS is used in a construction in which it is shielded from direct fire, the fire class of that construction can reach class B (with additional: s1 d0) (Kemisol, 2004).

Water vapour resistance factor

For EPS the μ depends on the density of the product and therefore ranges from μ = 20 – 100.

Practical application

EPS is versatile in its applications. It is used for the insulation of (cavity) walls, roofs and concrete floors. EPS is also used as a casting mould for concrete foundations of buildings. The panels are rigid and therefore capable of supporting themselves. The compressive strength of EPS increases with its density and ranges from almost none (at 5 kg/m^3) to $0,6 N/mm^2$ at 80 kg/m^3. When the EPS pearls are not bonded together to create panels or other forms, the loose pearls can also be used to fill existing cavity walls.

Price

EPS is produced by many companies. This means that a price comparison can be done between many products. The company Isobouw provide products to be used in cavity walls: Isofort (λ_D = 0.035W/m·K) and Polyfort (λ_D = 0.027W/m·K). The low λ_D of Polyfort is reached by a reflective foil on side of the panels (Isobouw, 2011a). A second company is Knauf, which also provides EPS panels. These panels do not have a reflective coating and therefore a λ_D of 0.037W/m·K and 0.038W/m·K (Knauf, 2011). The prices of the different products and their thickness are presented in table 4.1.

table 4.1 prices (exl. VAT) and thickness of EPS products to reach Rc=3.5 (Knauf, 2011 & Isobouw, 2011a)

Product	Producer	λ_D [W/m·K]	Product thickness [mm]	Price [€/m^2]	Flame retardant
Isofort	Isobouw	0.035	140	8.60	HBCD
Polyfort	Isobouw	0.027	93	17.35	HBCD
Therm 80	Knauf	0.037	130	9.90	HBCD
Therm 60	Knauf	0.038	130	8.90	HBCD

4.1.2 Extruded polystyrene (XPS)

figure 4.1.2 XPS panels (DOW, 2009)

Production
XPS is produced from the same base materials as EPS and therefore also has crude oil at its basis. The production process of XPS is only slightly different from EPS. Like EPS, polystyrene granulate is created with either a hydrocarbon or CO_2 as a blowing agent. Instead of heating the polystyrene granulates with steam, they are fed to an extruder, in which the granulate is heated. The extruder produces a continuous length of polystyrene through a rectangle mould, creating a long rectangle strip, suitable for cutting panels (figure 4.1.2). This polystyrene expands because of the pressure difference between the extruder and its surrounding. By using an extruder, a closed cell structure is obtained (Jelle, 2011). For XPS the same flame retardant is used as for EPS.

Thermal conductivity and density
Due to the closed cell structure in which the blowing agent is trapped, a somewhat lower thermal conductivity is reached. For XPS, the thermal conductivity ranges from 0.025W/m·K to 0.040W/m·K. The density of XPS ranges from 15 to 80 kg/m^3. Another advantage of the closed pore structure is the high compressive strength at a relatively low density: 0,7N/mm^2 at 45kg/m^3 (Bouwcenter, 2007, Papadopoulos, 2005, DOW, 2009).

Fire class
The fire class (when treated with a fire retarder) of XPS is E (Knauf, 2008).

Water vapour resistance factor
Because the structure of XPS is different than the structure of EPS, the µ-value is of the materials is different. For XPS, the µ = 80-300.

Practical application
Like EPS, XPS has a wide variety of applications. It can be used for the insulation of every element of the building envelope (Bouwcenter, 2007). However, because the material is extruded, no polystyrene pearls are created. XPS can therefore not be used to insulate existing cavity walls by blowing the material inside the air cavity.

Price
For XPS, the price of two products suitable for cavity wall insulation will be calculated. The first product is from DOW: Wallmate CW-A with a λ_D of 0.035W/m·K. This thermal conductivity will result in a layer of at least 119mm. Because the maximum thickness of the product is 100mm, this means that two product have to be put over each other to form a thick enough layer. The second product is Styrodur, produced by BASF. This product has a λ_D between 0.031 and 0.040W/m·K, depending on the product thickness (the thinner the product, the lower the thermal conductivity). A third product that is taken into account is Polyfoam D-350TG from Knauf (λ_D=0.029W/m·K). With the found λ_D and the price catalogues of the different products, the price of reaching R_c=3.5 can be determined. The result are given in table 4.2.

table 4.2 Prices (exl VAT) of XPS products to reach R_c=3.5 (Knauf, 2011 & Albintra, 2010 & Ravago, 2011a)

Product	Producer	λ_D [W/m·K]	Product thickness [mm]	Price [€/m^2]	Gas in cells	Flame retardant
Styrodur 3035 CS	BASF	0.033	2x60	18.72	Air	HBCD
Styrodur 3035 CS	BASF	0.038	140	23.10	Air	HBCD
Wallmate CW-A	DOW	0.035	2x60	21.24	Isobutane	HBCD
Polyfoam D-350TG	Knauf	0.029	2x50	18.00	1,1-Difluoroethane	HBCD

4.1.3 Phenol formaldehyde (PF)

figure 4.1.3 PF panel (Kingspan, 2011)

Production
Phenol formaldehyde is used to produce rigid foam panels. The used base products are phenols and formaldehyde. Phenol formaldehyde is also called 'Resol'. PF can be recognized by its distinctive red colour (see figure 4.1.3). For the production of foam, the phenols and formaldehyde are mixed together with a blowing agent and catalysts. The heat from the chemical reaction and the blowing agent create a very fine closed cell structure in which the blowing agent is captured.

Thermal conductivity and density
The cell structure of PF is finer than the structure of PUR and PIR. The thermal conductivity of PF is therefore around 0.021W/m·K at a density between 35-40kg/m^3 (VIBE, 2007 & Kingspan, 2011). The range in values is small, and therefore, most products are rigid panels.

Fire class
The PF-Foam has a fire class E or F. Most products however have a layer or lining of a different material, causing the fire class of these products to be in between B and D (Kingspan, 2009).

Water vapour resistance factor
The μ-value for the foam itself is in between 30-50. However, when an extra layer of material is added, (PE or aluminium foil for instance) the value changes.

Practical application
The rigid PF panels can be used to insulate all the elements of the building envelope.

Price
A product made of PF-foam is the Kingspan Kooltherm K8 panel. It is made of PF-foam with perforated aluminium foil on both sides. This gives the panel a λ_D of 0.021W/m·K. This low thermal conductivity results in a needed thickness of only 72mm in order to reach R_c = 3.5. The price is given in table 4.3.

table 4.3 PF-Foam product prices (exl. VAT) in R_c = 3.5 cavity wall (Kingspan, 2011)

Product	Producer	λ_D [W/m·K]	Product thickness [mm]	Price [€/m^2]	Blowing agent
Kooltherm K8	Kingspan	0.021	76	23.00	Pentane

4.1.4 Polyurethane (PUR)

figure 4.1.4 Rigid PUR panel (Recticel, 2011a)

Production

For the production of PUR, two basic chemicals are needed: isocyanate and (polyether) polyol. By mixing the two chemicals, an expansion reaction is started in which PUR is formed. This expansion reaction is created by adding a blowing agent to the mixture. The heat from the reaction between the polyol and the isocyanate vaporises the blowing agent, creating a foam. During the reaction, the pores are filled with an expansion gas, such as CO_2 or pentane (Proklima, 2009). From the created product, rigid panels are cut (see figure 4.1.4). Next to panels, PUR is also available as a caulking foam to close openings and seams in between insulating materials or other building materials.

Thermal conductivity and density

PUR contains a closed cell structure in which the blowing agent is sealed. Because of this very fine structure, the thermal conductivity of PUR is between 0.022 and 0.035 W/m·K and a density varying from 30-160 kg/m^2 (Jelle, 2011, Technisol, 2005). When the density increases, the thermal conductivity increases as well.

Fire class

The fire class of PUR ranges from D to F. This depends on any extra layers of fire proof materials that are added to the panels, like reflective foils (Recticel, 2011b &Technisol, 2005). The PUR foam itself has fire class F.

Water vapour resistance factor

For the foam, the μ = 50-100 (Recticel, 2011a).

Practical application

Insulating panels made from PUR can be applied to all elements of the building envelope. Because of the low thermal conductivity, the material is able to reach high thermal resistances with a relatively low material thickness. Another important aspect is that PUR can also be injected into existing cavity walls, by using the existing openings and some extra holes. The entire air cavity can be retrofitted with PUR foam.

Price

When PUR is used in cavity walls in the form of panels, the λ_D of such panels can be as low as 0.023W/m·K. A product with this thermal conductivity is Eurowall, produced by Recticel. The low thermal conductivity is partly due to the reflective foil on one side of the panel. Because of the low λ_D the thickness of the material needed to reach R_c=3.5 is 79mm according to the calculation method of section 1.4. In table 4.4 the calculated thickness and price of this product when used in a cavity wall with R_c = 3.5 are given.

table 4.4 Price (exl. VAT) of PUR panels when used to reach Rc_c = 3.5 (Deschacht Plastics, 2011a).

Product	Producer	λ_D [W/m·K]	Product thickness [mm]	Price [€/m^2]	Blowing agent
Eurowall	Recticel	0.023	82	24.91	Pentane

4.1.5 Polyisocyanurate (PIR)

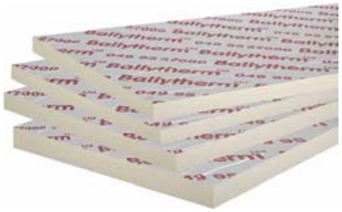

figure 4.1.5 PIR panels (Ballytherm, 2007)

Production

The production of PIR is almost the same as the production of PUR. For the production of PIR a polyester polyol is mixed with an excess of isocyanate (methylene diphenyl diisocyanate). This excess of isocyanate causes the isocyanate to first react with itself, creating ring structured polymers. The ring structure and left over isocyanate then react with the polyol. By adding a blowing agent, the end product PIR is obtained (Bouwcenter, 2007). From the finished PIR product, panels are cut. 95% of the PUR/PIR production in Germany is produced with pentane as a blowing agent. As a flame retardant, Tris(2-Chloro-1-Methylethyl) Phosphate (TCPP, TMCP) or Tris(2-chloroethyl)phosphate (TCEP) (Wecobis, 2011; European flame retardants association, 2006)

Thermal conductivity and density

The structure of PIR consist of a closed cell structure, similar to PUR. The thermal conductivity can however be lower than of PUR: 0.020-0.035W/m·K, but the most common values are around >0.023 W/m·K (VIBE, 2007). The density of PIR equals the density of PUR. The density for panels ranges from 28-40kg/m^3 (Unilin, 2011 &

Fire class

The fire class for PIR is equal to PUR (class D to F, dependable of the used product, but F for the foam itself) (Recticel, 2011b).

Water vapour resistance factor

Same as for PUR, $\mu = 50 - 100$.

Practical application

PIR can be used in the same way as PUR with the difference that PIR cannot be used to insulate existing cavity walls. There is no PIR foam that can be injected into existing cavity walls, because of the difference in the production process compared to PUR.

Price

To determine the price of PIR cavity wall insulation, four products are looked into. All four products (panels) have two things in common: their λ_D=0.023W/m·K and all the products have a tongue and groove systems, to make the panels fit tightly. The four producers are Unilin, Xtratherm, Kingspan and Iko. Along with the calculation method of section 1.4 and the price catalogues, the product price can be calculated. The results are depicted in table 4.5. Interestingly, all the panels have the same product thickness. It could be that producers try to anticipate on building regulation.

table 4.5 Price (exl. VAT) of PIR products to reach R_c=3.5 (Unilin, 2011; Ravago, 2011b; Kingspan, 2011; Deschat Plastics, 2011b)

Product	Producer	λ_D [W/m·K]	Product thickness [mm]	Price [€/m^2]	Blowing agent
Utherm Wall R	Unilin	0.023	82	20.51	-
Xtratherm XT-CW	Xtratherm	0.023	82	21.46	-
Thermawall TW 50	Kingspan	0.023	82	23.50	Pentane
Enertherm	Iko	0.023	82	22.45	-

4.1.6 Urea formaldehyde (UF)

figure 4.1.6 UF-foam injected into cavity wall (Br-architect, 2010)

Production

Urea formaldehyde is made on site by adding mixing the urea formaldehyde resin with a hardener and a blowing agent. This mixture results in foam, that expands due to the blowing agent. No panels or other types of insulating materials are produced from the foam, since it is blown directly into empty cavity walls (see figure 4.1.6) or other structures that need to be insulated (Bouwcenter, 2007).

Thermal conductivity and density

The density of the foam is around 12kg/m^3. The thermal conductivity of UF-foam is between 0.036 and 0.045W/m·K (Thermecon, 2007).

Fire class

UF-foam has a fire class in between D and E (d-isolatie, 2010).

Water vapour resistance factor

For UF-foam the μ-value ranges from 1.5 and 2.4 (Thermecon, 2007 & d-isolatie, 2010).

Practical application

As mentioned above, the UF-foam is used for the retrofitting of existing cavity walls. However, due to the fact that the foam shrinks after being injected into the cavity, cracks may appear in the foam, a disadvantage of using UF-foam.

Price

Not used anymore in the Netherlands. This is because the foam shrinks during the drying process, causing ruptures in the foam and eventually the foam getting loose from the walls. In figure 4.1.7 the ruptures in the UF-foam are visible, after the out wall of the cavity wall is removed. Next to the rupturing of the foam, formaldehyde continues to diffuse out of UF-foam during its lifetime (Meeusen, 2006).

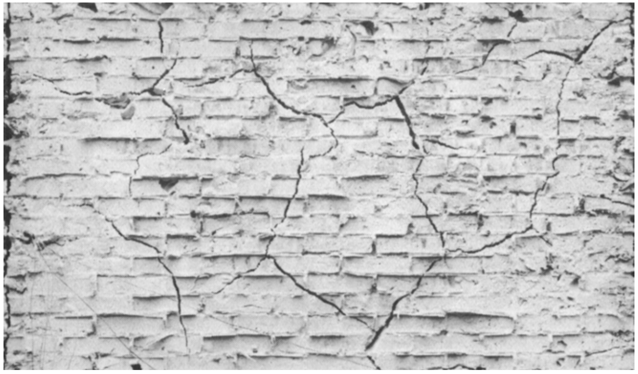

figure 4.1.7 cracks in UF-foam visible after the outer wall is removed (Meeusen, 2006).

5 Organic insulating materials: renewable

The insulating materials covered in this section are based upon renewable resources, in other words, the main material is bio-based. Since many plants contain fibres for their strength, it is no surprise that almost all the materials in this section are fibrous. Expanded cork is the only exception, the material is cellular. The following materials are treated within this section:

- Fibrous
    - Cellulose (paper wool)
    - Flax (flax wool)
    - Hemp (hemp wool)
    - Recycled cotton
    - Sheep wool
    - Wood wool
    - Coconut
- Cellular
    - Cork

5.1 Fibrous

5.1.1 Cellulose (paper wool)

figure 5.1.1 cellulose panel (Homatherm, 2011a)

Production
Cellulose insulating material is produced from recycled paper or wood fibre mass. This waste is shred and unravelled, so that the cellulose fibres are obtained. The obtained cellulose fibres have a wool like structure. In order to make the cellulose fibres moisture and flame retardant, boric acid and borax are added. To give more strength to the panels, polyolefin fibres are added to the cellulose fibres. From the treated fibres, panels, rolls and flocks are produced (Jelle, 2011 & Homatherm, 2011). An example of such a panel can be seen in figure 5.1.1.

Thermal conductivity and density
The thermal conductivity of cellulose lies between 0.038 and 0.040W/m·K. Its density ranges from 30kg/m^3 for flocks to 70kg/m^3 for panels (Isofloc, 2011 & Homatherm, 2011a).

Fire class
The fire class of cellulose panels and flocks is E (Isofloc, 2011a & Homatherm, 2011a).

Water vapour resistance factor
For cellulose panels the µ is between 2 and 3 where for flocks this value lies between 1 and 2, so only a minor difference.

Practical application

Newly build cavity walls can be fitted with cellulose panels (if protected against rain water). Cellulose cannot be used for the insulation of flat roofs or for the insulating on the outside of the building envelope (wet render systems) (Bouwcenter, 2007). Its compressive strength is too low to support a finish layer. Dry cladding systems also do not provide enough shelter for the panels to be used in such an application.

Price

Panels of cellulose fibres are produced by Homatherm. The panels have a λ_D of 0.039. Although the panels can be used within cavity walls, the producer discourages this (Vijfwinkel, 2011). This is because the material is not water resistant. When the cellulose panels are used within a cavity wall, they should be covered with a plastic (PE) foil to protect them from rain water. The thermal conductivity of the panels is 0.039W/m·K. According to the calculation in section 1.4 this gives a product thickness of 140mm. The price of the material per m^2 can now be calculated. The resulting value is given in table 5.1.

table 5.1 Cavity wall insulation to R_c=3.5 with cellulose products (Homatherm, 2011b)

Product	Producer	λ_D [W/m·K]	Product thickness [mm]	Price [€/m^2]	Flame retardant
FlexCL	Homatherm	0.039	140	24.60	Boric acid

5.1.2 Coconut

figure 5.1.2 coconut panels (Van Avermaet, 2011a)

Production

Coconut insulating materials are produced from fibres obtained from the coconut husks. The fibres are obtained by soaking the husks in water and letting everything but the fibres rot away (the coconut fibres do not rot). This process is done prior to shipping the fibres to the process plants. In the process plants the fibres are fulled to produce panels and rolls (Hasselaar, 2004).

Thermal conductivity and density

The thermal conductivity of coconut based materials ranges from 0.040 to 0.045 W/m·K at a density around 140kg/m^3 (Bouwcenter, 2007 & Hasselaar, 2004).

Fire class

Coconut has a fire class E (Van Avermaet, 20011b)

Water vapour resistance factor

Coconut panels have a μ value in between 1 and 10.

Practical application

According to the Bouwcenter coconut panels has a very limited area of use. It can only be used for cavity wall insulation for the insulation of floors (both wood and concrete). Also, there are just a few suppliers of the material.

Price

Coconut panels are only available in thin panels. The maximum thickness that Van Avermaet (a producer of coconut panels) produces is 25mm. Since this material has a λ of 0.045, 7 layers of coconut are needed to reach R_c = 3.5. This results in the price given in table 5.2.

table 5.2 coconut product price (exl. VAT) when used in cavity wall with R_c=3.5 (Bio Home, 2011)

Product	Producer	λ_D [W/m·K]	Product thickness [mm]	Price [€/m^2]
Kokosplaat	Van Avermaet	0.045	7x25	84.35

5.1.3 Flax (flax wool)

figure 5.1.3 Flax wool panel (Ecobouwen, 2011)

Production

Flax panels and rolls are produced from the long fibres obtained from flax plants. Both the plant and its roots are used for the production of flax. After the harvest, the plants are dried and the stalks are separated from the seeds. The fibres from the stalks are impregnated with ammonium phosphate or borax to make them fire resistant and resistant against organisms. The impregnated fibres are torn apart to create a wool like structure. With the use of a binding agent (polyester support fibres or corn/potato starch) rolls and panels are produced (Hasselaar, 2004)

Thermal conductivity and density

Flax wool has a density of 28kg/m^3. Its thermal conductivity ranges from 0.035 to 0.040 W/m·K (Hasselaar, 2004 & Isovlas, 2010).

Fire class

The fire class of flax is C (Isovlas, 2010)

Water vapour resistance factor

For flax, the water vapour resistance factor μ = 1-2 (Hasselaar, 2004).

Practical application

Apart from flat roof insulation, flax wool products can be used for the insulation of every element of a building's building envelope. However, since flax wool is produced in rolls and panels, it is not possible to used at a retrofitting material for cavity walls (it cannot be blown into the cavity).

Price

A producer of flax wool is Isovlas. Isovlas is not as strong as glass or rock wool, which means it has to be supported by 8 fasteners/m^2. The λ_D of the flax wool produced by Isovlas is 0.035W/m·K. The needed thickness within a cavity wall of R_c = 3.5 according to the calculation of section 1.4 is 120.1mm. A Isovlas panel with a thickness of 120mm would is therefore not sufficient. The next product thickness is 130mm, of which the price per m^2 can be found in table 5.3.

table 5.3 Price (exl. VAT) of flax when used to reach R_c=3.5 in a cavity wall (Isovlas, 2011).

Product	Producer	λ_D [W/m·K]	Product thickness [mm]	Price [€/m^2]	Flame retardant
Isovlas PN	Isovlas	0.035	130	15.18	Ammonium phosphate

5.1.4 Hemp (hemp wool)

figure 5.1.4 hemp insulation products (Hock, 2009)

Production

The production of hemp wool is similar to the production of flax wool. After the hemp is harvested, it is dried. The dried hemp plant is separated into wood, fibres, leafs, seeds and leftover dust. For the production of insulating materials, the fibres are of importance. The fibres are used to create a wool. To hold the wool together, strengthening polyester fibres or (corn/potato) starch fibres are used. The hemp wool with polyester fibres cannot be composted and should be treated as household waste. (Holzhey, 2011). By the addition of ammonium phosphate or borax the wool is impregnated to improve the fire resistance and the resistance against organisms (Hasselaar, 2004). From the wool, flocks, rolls and panels are made (see figure 5.1.4).

Thermal conductivity and density

Hemp has a thermal conductivity between 0.038 and 0.040 W/m·K. Its density ranges from 30 to 42kg/m^3 (Hock, 2009).

Fire class

Hemp wool has a fire class E. (Hock, 2009)

Water vapour resistance factor

The μ for hemp wool is between 1 and 2 (Hasselaar 2004 & Hock, 2009).

Practical application

The practical applications for hemp are the same as for flax. This means that apart from insulating on the outside of the building, all elements of the building envelope can be insulated using hemp. An advantage of hemp over flax is that it is also produced in flocks.

Price

For hemp wool, two producers are taken into account: Hock and Steico. The hemp wool from Hock has a λ_D of 0.040W/m·K. Hock produces two types of hemp wool: one with polyester fibres (Thermo-Hanf Premium) and one with corn starch fibres (Thermo-Hanf Plus). This λ_D results in a minimum thickness of 135mm according to the calculation method of section 1.4. The same is done for the product ‘Steicoflex’ from Steico, which has a λ_D of 0.038W/m·K. The accompanying product thickness and price can be found in table 5.4.

table 5.4 Hemp wool product prices (exl. VAT) in cavity wall with R_c=3.5 (Hock, 2011 & Steico, 2011)

Product	Producer	λ_D [W/m·K]	Product thickness [mm]	Price [€/m^2]	Support fibres	Flame retardant
Thermo-Hanf Premium	Hock	0.040	140	15.13	Polyester	Soda
Thermo-Hanf Plus	Hock	0.040	140	19.45	Corn starch	Soda
Steicoflex	Steico	0.038	140	18.40	polyolefin	Ammonium phosphate

5.1.5 Recycled cotton

figure 5.1.5 Recycled cotton panel (VRK isolatie, 2011)

Production
Recycled cotton is produced from clothing that is disposed of by consumers. This clothing is collected, after which the hard items (e.g. buttons, zippers) are removed. The clothing is than shredded into fibres. By adding polyester binding fibres, panels and rolls and flocks can be produced. The ratio clothing/binding fibres is 85/15 (in which the 85% is 70% cotton and 15% wool/acrylic). Next to that, Zink Pyrithione is added (<1%) against organisms. The used flame retardant in Metisse insulation is a natural salt. The insulation panels go through a bath in which the salt is dissolved. After drying, the salt sticks to the fibers making them flame retardant. Which salt is used exactly is confidential information (VRK isolatie, 2011).

Thermal conductivity and density
The thermal conductivity of the material is 0.038W/m·K at a density of around 18kg/m^3 (VRK isolatie, 2011).

Fire class
Due to impregnation of the material, its fire class is E (VRK isolatie, 2011).

Water vapour resistance factor
Recycled cotton is a vapour open material, which means it has a water vapour resistance factor between 1 and 5.

Practical application
The recycled cotton flocks can only be used in horizontal application, making them not suitable for cavity wall or pitched roof after insulation. The rolls and panels can be used for the insulation of the entire building envelope with the exception of flat roofs. However, when the material is used in cavity walls or in roofs, it should be covered a waterproof foil, so the material will not get wet.

Price
A product made of recycled cotton is Metisse. Metisse is available in rolls, panels and flocks. Its thermal conductivity is 0.038, which according to section 1.4, gives it a needed thickness of 130mm. Both the rolls and panels are available in that thickness, which results in the price given in table 5.5. The price for panel or roll is the same per/m^2.

table 5.5 price (ex VAT) of recycled cotton insulating material in cavity wall with Rc=3.5 (Ecologisch, 2011)

Product	Producer	λ_D [W/m·K]	Product thickness [mm]	Price [€/m^2]	Support fibres	Flame retardant
Metisse MT+ panel	Le Relais	0.038	140	19.32	Polyester	-
Metisse MT+ roll	Le Relais	0.038	140	19.32	Polyester	-

5.1.6 Sheep wool

figure 5.1.6 Sheep's wool (Doscha, 2011)

Production

After the wool is shorn from the sheep (1 sheep produces 2.5-4kg of wool/year), its needs to be cleaned to wash away dirt and to degrease the wool. To align the fibres into the same direction, the wool is carded. Sheep do not have layers of wool as thick as 10cm on them, which means that in order to reach the final product thickness, multiple layers of wool are fulled[2] to fix the layers. To produce a sturdy product, the first layer of wool is densely felted. This is done with a dark wool, so that this layer is easy to recognize (see figure 5.1.6). Sheep wool is available in rolls. The main material in sheep wool is keratin. Because keratin is a protein, sheep wool must be treated to protect it against mot's and insects. This is done by adding either Mystox MP or Mitin FF. Another way of producing the sheep wool is to add melting fibres to the wool, have these fibres melt around the sheep wool. (Doscha, 2011 & Sheep Wool Insulation, 2011).

Thermal conductivity and density

Sheep wool has a thermal conductivity of 0.035 to 0.040W/m·K and a density ranging from 25 to 60kg/m^3. (Doscha, 2011 & VIBE, 2007).

Fire class

The fire class of sheeps wool is E (Doscha, 2011).

Water vapour resistance factor

For sheep wool the water vapour resistance factor is 1,4 according to Doscha (2011) and between 1 and 2 according to Hasselaar (2004).

Practical application

Sheep wool can be used for the insulation of pitched roofs, newly built cavity walls, wooden floors and for the insulation of timber frame constructions. The material is not very sturdy, which means that it needs to be mounted in a way that there is enough support for the rolls.

Price

A producer of sheep wool rolls that can be used within a cavity wall is Doscha. Their products, Doscha DB has a λ_D of 0.035W/m·K. This results in a necessary thickness of 119mm. The needed product and price can be found in table 5.6.

table 5.6 Sheep wool insulation product price (exl. VAT) (Groene bouwmaterialen, 2011)

Product	Producer	λ_D [W/m·K]	Product thickness [mm]	Price [€/m^2]
Doscha DB	Doscha	0.035	120	24.00

---

[2] Fulling is a technique with which the wool is cleansed and condensed, to give it a higher density and water resistance.

5.1.7 Wood wool

figure 5.1.7 Wood wool (Homatherm, 2010)

Production

For the production of wood wool, waste wood from the pine wood industry (bark, sapwood, saw residues) and forestry are used. The waste wood is chipped into small pieces. Consequently the chips are soaked with steam at a pressure of 3-8 bar. The soaked chips are grinded to produce fibres. From these fibres, panels are produced. To produce the panels, the fibres are bonded with their own lignin, by pressing them together and drying them in a drier. The panels can also be produced in a dry process, in which a binding resin (PMDI) is used. The produced panels have a thickness between 8-30mm. For the insulation of buildings thicker panels are needed. These thicker panels are made by gluing multiple thin panels on top of each other (VIBE, 2007, Pavatex, 2011a).

Thermal conductivity and density

Wood wool's thermal conductivity ranges from 0.038 to 0.058W/m·K. The thermal conductivity depends on the purpose of the material. The thick insulating panels for roofs, walls and floors (like the panel in figure 5.1.7) have the lowest thermal conductivity at a density of 55 to 140kg/m^3 (for comparison, particle board has a density around 660kg/m^3 with a thermal conductivity around 0.17W/m·K). Panels with a higher density are used to prevent cold bridges. Due to the higher density, the thermal conductivity also increases. (Pavatex, 2011b).

Fire class

Wood wool panels have a fire class E (Pavatex, 2011b).

Water vapour resistance factor

According to Pavatex, their wood wool has a μ-value of 5 (Pavatex, 2011b).

Practical application

As mentioned above, wood wool can be used to insulate all the elements of the building envelope, including cold bridges and wet render systems (Pavatex, 2011b).

Price

A wood wool product that can be applied in cavity walls is Pavatherm-plus+, because this product has a waterproof layer on one side. The λ_D of the product is 0.045W/m·K. This means a minimal material thickness of 152mm is needed to reach $R_c = 3.5$. When Pavatherm is used, this means that a double layer is needed of 2x80mm, since the maximum product thickness is 120mm. Homatherm also produces panels that can be used within cavity walls: the HDP-Q11 standard with λ_D=0.038W/m·K. In table 5.7, the price per m^2 of the different panels can be found.

table 5.7 Price (exl VAT) of wood wool products in R_c=3.5 cavity wall (Pavatex, 2011c & Homatherm, 2011b)

Product	Producer	λ_D [W/m·K]	Product thickness [mm]	Price [€/m^2]	Flame retardant
Pavatherm-plus+	Pavatex	0.045	2x80	37.83	Ammonium polyphosphate
HDP-Q11 standard	Homatherm	0.038	140	26.60	Ammonium polyphosphate

5.2 Cellular

5.2.1 Cork (expanded)

figure 5.2.1 cork panel (Van Avermaet, 2011c)

Production

Cork is produced from the cork oak. Every nine years, the bark is removed from the tree (see figure 5.2.2). This does not harm the tree because the bark renews itself. The harvested bark is placed into an autoclave (like is done with calcium silicate). Inside the autoclave, the cork cells expand due to the addition of steam and the high temperature and pressure inside the autoclave. The cork is bonded into blocks by its own resins (suberin). From the blocks, flakes and panels can be produced. During the autoclave process, cork obtains a dark colour (Van Avermaet, 2011c). A finished cork panel can be seen in figure 5.2.1.

figure 5.2.2 removing the bark from the cork oak (Nature of the game, 2011)

Thermal conductivity and density

The thermal conductivity of cork lies between 0.037 and 0.043W/m·K (VIBE, 2007, Bouwcenter, 2007). Its density is around 100kg/m^3 for granules and 120kg/m^3 for panels. (Van Avermaet, 2011c).

Fire class

The fire class of cork is E (van Avermaet, 2011c)

Water vapour resistance factor

Because cork is a cellular material, the water vapour resistance factor of the material is higher than that of the other renewable materials: μ = between 5 and 30 (Van Avermaet, 2011c).

Practical application

Cork insulation can be applied in cavity walls, roofs and under floors. It can also be used to insulate walls from the inside.

Price

Expanded cork panels are available in two types: one with and one without tongue and groove. Both panels have a thermal conductivity of 0.040W/m·K. This results in a minimum material thickness of 135mm. Since this thickness is not available, two layers of cork are needed of 60 and 80mm thick. In case of cork granuless, the factor for 'in-situ' placement has to be used. This results in a layer thickness of The resulting price is given in table 5.8.

table 5.8 Price (exl. VAT) of cork panels in cavity wall of R_c = 3.5. (Bio Home, 2011)

Product	Producer	λ_D [W/m·K]	Product thickness [mm]	Price [€/m^2]
Cork without T&G	Van Avermaet	0.040	60+80	40.79
Cork with T&G	Van Avermaet	0.040	60+80	44.68
Cork granules	Van Avermaet	0.040	164	25.58

6 New technology materials

New technology materials are insulating materials are not used at a large scale yet, because the materials are too new or too expensive. The materials/technologies covered in this section are:

- Thermosheets / thermoscushions
- Expaneded Polylactic acid
- Aerogel
- Vacuum panels

6.1 Foil

6.1.1 Thermosheets

figure 6.1.1 thermosheets underneath a concrete floor (Tonzon, 2011a)

Production

Thermo sheets are sheets made of a thin (12-19µm) polyester foil, covered with a reflective aluminium surface.

Properties

The principle behind thermo sheets is trapping air in between foils, creating pillows. This results in a thermal conductivity that ranges between 0.029-0.045W/m·K. Because foils are used, the density at which this thermal conductivity is reached, is low: between 3-3,5 kg/m^3 (Bouwcenter, 2007 & Tonzon, 2008).

Practical application

Thermo sheets can be used to insulate walls and roofs from the inside. This can be done during construction, or during renovation. Floors can also be insulated with thermo sheets, but this requires the sheets to be mounted underneath the floor, in the crawl space. The thermo sheet must not be punctured. The more layers (and therefore spaces) used, the better the total thermal resistance. In figure 6.1.1 the sheets are used to create air cushions underneath a concrete floor. Also here, the number of cushions determines the overall thermal resistance. For a wooden floor, the foil and cushions are fixed by stapling the foil or cushions to the wooden beams and ceiling the end and edges with tape. The same process can be used for roofs. Underneath concrete floors the mounting can be done by gluing an adhesive strip to the concrete to which the sheets or cushions are adhered. Another option is to use plastic plugs which are drilled into the concrete. For the insulation of walls, the sheets are mounted upon battens of around two centimetres thick. Be creating multiple layers with battens and sheets, a higher thermal resistance is obtained (Tonzon, 2011b).

Fire class

The used foils don not have fire classification. This is because of the thickness of the foils. The foils are so thin, that they are not capable to set fire to wood or other materials (Willemsen, 2011). The foil is therefore flammable, which would put it into class F.

Water vapour resistance factor

The μ-value of the foils is high. According to Tonzon, the μd of their foils is 130m, at a thickness of $19 \cdot 10^{-6}$m. This gives a μ-value of $6.8 \cdot 10^{6}$, which can be considered as vapour tight, almost no water vapour can pass through the foils.

Price

The thermosheets and cushions cannot be used for the insulation of cavity walls.

6.2 Cellular

6.2.1 Expanded polylactic acid

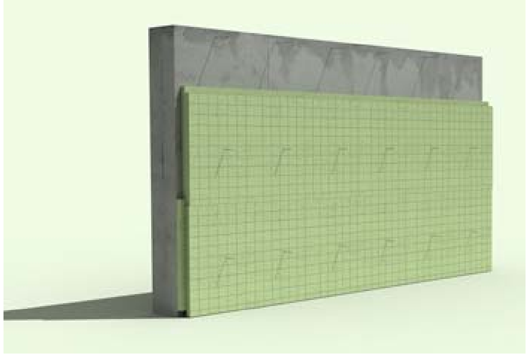

figure 6.2.1 Biofoam used for cavity wall insulation (Isobouw, 2011b).

Production
The production of expanded polylactic acid (EPA) is comparable to the production of expanded polystyrene. Instead of styrene, lactic acid is used. This lactic acid is obtained from renewable sources like sugarcane or cassava (Cobouw, 2011). The sugar cane is refined into sugar, which is fermented into lactic acid. From the lactic acid, lactide is produced. This lactide is polymerised into polylactic acid beads the size of sugar granules (Synbra, 2011a). These beads are expanded with temperature and addition of CO_2, forming pearls (like in the production of EPS, only without the use of pentane). The expanded polylactic acid beads can be bonded into panels, which can be used for insulation (Cobouw, 2011).

Properties
EPA has a thermal conductivity of around 0.034W/m·K at a density of 35kg/m^3 (Synbra, 2011b). EPA is a biodegradable material, which means that it can be composted. However, this composting has to be done under industrial conditions (high temperature, enough water and bacteria) before composting will take place. This means that the material should be collected in the end of life or waste phase, so it can be composted under the correct conditions.

Practical application
The loose EPA pearls can be blown into existing cavity walls or other existing cavities. Next to that, EPA panels are going to be produced that can be used for the insulation of roofs, walls (cavity and wet render systems) and maybe even floors.

Fire class
The fire class of EPA is B, but this is when the product is used ‘within application’. This means that the real fire class of the material is lower, around E or F (same as for EPS).

Water vapour resistance factor
Same as EPS, µ = 20-100.

Price
The insulating panels are not yet on the market.

6.2.2 Aerogel

figure 6.2.2 Aerogel impregnated textile (Aspen Aerogels, 2010)

Production
The base material for aerogel is silicon. To produce aerogel, two steps can be defined: making the gel, and drying the gel. The first step is to make the gel. This done by adding water to silicon alkoxide precursors within an ethanol solution. The gel is created by the reaction of water with alkoxide, forming SiO_2. In a supercritical drying process, the fluids are removed, keeping the SiO_2 structure intact. The structure is filled with gas (air) To make aerogel suitable for insulating, a textile made of glass- and polyester fibres can be impregnated with the gel before drying. After the supercritical drying, the aerogel textile can be used for insulating purposes. The aerogel textile is available in rolls (Sattler, 2006 & Aspen Aerogels, 2011). Another option is aerogel granules that can be used for the after insulation of for instance cavity walls.

Properties
The aerogel textile has a thermal conductivity of 0.013W/m·K. Its density is 150kg/m^3 (Aspen Aerogels, 2010). The granules have thermal conductivity of 0.021W/m·K at a density of 100kg/m^3 (Innodämm, 2011)

Practical application
When the aerogel is used to impregnate textile it can be used for the insulation of roofs, floor and walls, both exterior and interior. The aerogel textiles are glued to the surface that needs to be insulated. aerogel granules are blown into the cavity that needs to be insulated.

Water vapour resistance factor
Aerogel is a vapour open material. Its water vapour resistance factor is around between 2 and 3 for granules and 5.5 for the textile. (Innodämm, 2010 & Innodämm, 2011).

Fire class
The fire class of the aerogel impregnated textile is C. The fire class of aerogel itself is A1 (Innodämm, 2010 & LouRuis, 2010).

Price
Because of the low λ value of the impregnated textile, a thin layer of material is needed within a cavity wall: 46mm according to the calculation of section 1.4. An aerogel textile available on the market is Spaceloft, produced by Aspen Aerogels. Spaceloft comes in rolls of 5 or 10mm thick. This means that 5 layers of Spaceloft are needed to reach R_c = 3.5. When granules are used, a layer of 86mm is needed. The density of this layer is 95kg/m^3, because of the method with which the materials are blown in. This results in the price given in table 6.1.

table 6.1 price (exl VAT) of Aerogel textile and granules within a R_c=3.5 cavity wall (TSchopp, 2010 & Unser Bausatzhaus, 2009)

Product	Producer	λ_D [W/m·K]	Product thickness [mm]	Price [€/m^2]
Spaceloft	Aspen Aerogels	0.013	5x10	61.50
Aerogel granules	Innodämm	0.021	86	111.12

6.2.3 Vacuum insulation panels (VIP)

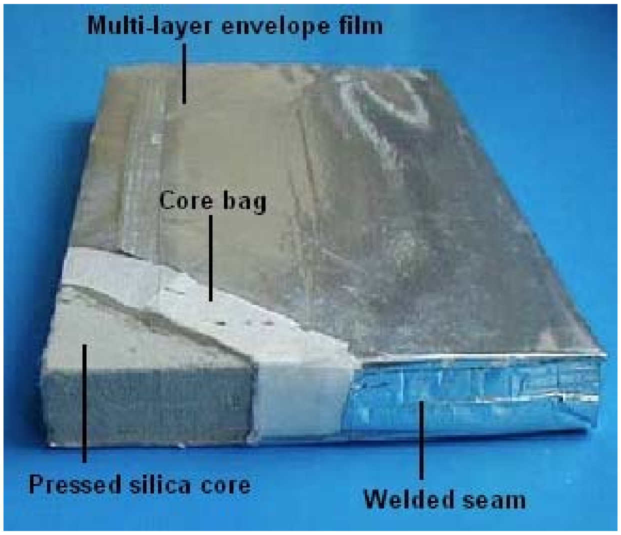

figure 6.2.3 structure of a VIP (Adjusted after: ECBCS Annex 39, 2010)

Production

The production of VIPs starts with creating a panel out of an open porous structure of fumed silica, which is a by product of high-purity silicon production for the electro technical industry. The fumed silica is compressed to a density of 200kg/m^3. This compression creates a pore size that is well below the mean free path of atmospheric gas molecules at internal pressures below 1 bar (Simmler and Brunner, 2005).

The created panel is wrapped in metalized polymer laminate layers. Since the core structure is porous, a vacuum can be applied to it. After this is done, the edges of the polymer layers are heat sealed to maintain the vacuum. The structure of a VIP can be seen in figure 6.2.3. For the porous core structure other materials can be used as well. However, for building insulation fumed silica is commonly used (ECBCS Annex 39, 2010 & Jelle, 2011).

Properties

The thermal conductivity of a VIP just after production is very low: around 0.004W/m·K. However, aging has a negative effect on the panels. This is because the envelope of the panels is not fully airtight. The increase in thermal conductivity over the lifetime of the panel therefore depends on the type of envelope used. In figure 6.2.4 the effect of different envelopes is plotted as a function of thermal conductivity and lifetime. Three different envelopes were tested, namely AF, MF1 and MF2. In total six panels were tested: three panels of 50x50x1 cm (AF-50, MF1-50 and MF2-50) and three panels of 100x100x2 (AF-100, MF1-100 and MF2-100). The structure of the different envelopes is described in figure 6.2.5. From the graph it is clear that the thermal conductivity increases strongly in the first years, after which for most VIP a slow increase is seen. According to Simmler an Brunner (2005), the most important mechanism of aging is gas permeation through the panel's envelope.

According to the ECBCS Annex 39 project, a thermal conductivity of 0.008W/m·K should be used when dimensioning VIP for building insulation. If the panels get aerated (punctured) the thermal conductivity rises to 0.020W/m·K according to Va-Q-tec, a producer of VIPs. Va-Q-tec gives a service life of 60 years for their panels (Va-Q-tec, 2011).

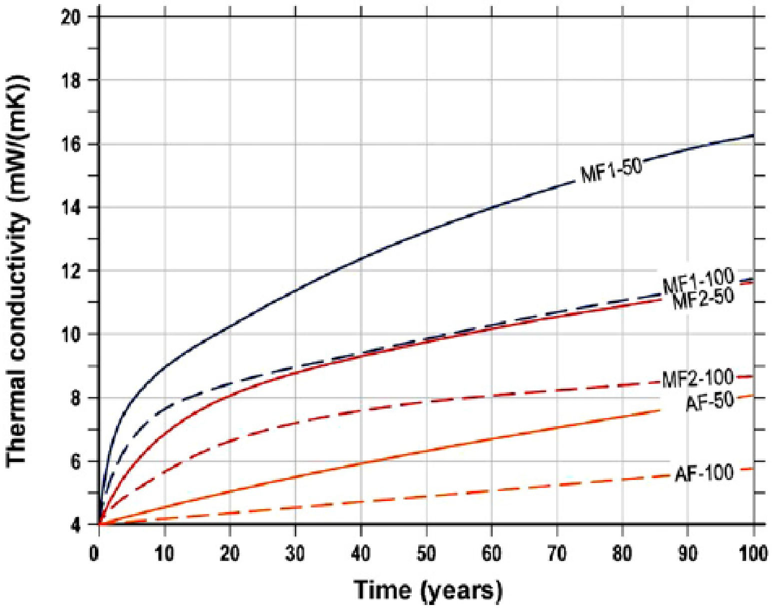

figure 6.2.4 increase of thermal conductivity over lifetime of VIP per envelope (Jelle, 2011)

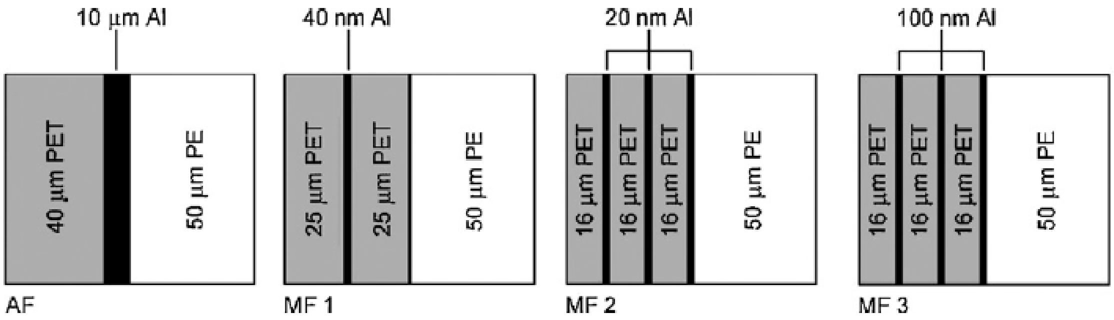

figure 6.2.5 structure of the VIP envelope (Jelle, 2011)

The density of the panels is between 180 and 210 kg/m^3 (Va-Q-tec, 2011).

Practical application

The panels can be used for the insulation of almost every element of the building envelope. Only existing cavity walls cannot be insulated with VIPs. Another important aspect of VIPs is that they cannot be cut into shape at the construction site and are very vulnerable to puncture. If a panel is punctured, air seeps in and destroys the vacuum, causing the thermal conductivity to increase.

Water vapour resistance factor

The water vapour resistance factor of the panels is almost infinite, since the panels are created to be sealed from their environment.

Fire class

The fire class of the core material is A2 (ECBCS Annex 39, 2010). A complete panel is covered in flammable polymer foils, giving it a fire class D.

Price

If the calculation method from section 1.4 is used with a thermal conductivity of 0.008W/m·K, a 30mm thick VIP is needed to reach R_c= 3.5. According to Jelle (2011), the price of a 6cm thick VIP is around 200€/m^2. This would mean that a VIP panel of half the thickness would cost 100€/m^2. The costs for VIPs with a λ of 0.008W/m·K presented in the for a ECBCS Annex 39 study are 34.32€/m^2 per m^2·K/W. In other words, the price of a VIP with a λ of 0.008W/m·K to reach a R value of 1 is 34.32€/m^2. In equation 1.6 of section 1.4 it is calculated that the insulating material must provide a thermal resistance (R_m) of 3.305m^2·K/W in order to reach the R_c=3.5 value. With the R_m of equation 1.6, the price of the VIP can be calculated by multiplying the value from the ECBCS Annex 39 study with 3.305. This results in a price of 113.4€/m^2 which is in agreement with the price presented by Jelle (2011). The German Institut Wohnen und Umwelt (IWU) of Darmstadt estimates the costs for VIPs to be between 90 to 172.5€/m^2. According to IWU the price depends on the type of VIP, a normal VIP without any extra protection would costs 90€/m^2, whereas a VIP packed in EPS would cost 120 to 172.5€/m^2 (IWU, 2009). An example of VIP packed in EPS can be seen in figure 6.2.6. Its application can be seen in figure 6.2.7. The panels can be finished with a render, making them very suitable for renovation.

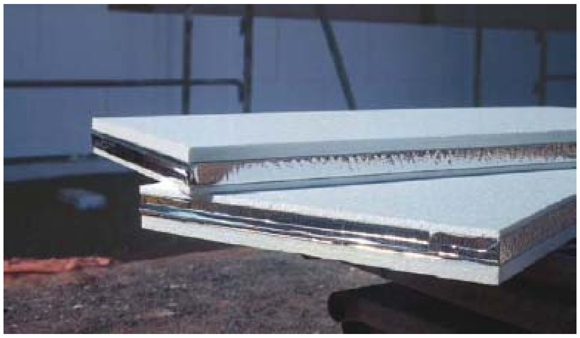

figure 6.2.6 VIP with packed in EPS (IWU, 2009)

figure 6.2.7 application of VIP on a dwelling (IWU, 2009)

7 References

Albintra, 2011. *Tariefblad Styrodur C.* [online] Albintra. Available at: <http://www.albintra.be/pages/products/B/tarieven/B201_n.pdf> [Accessed: 18 October 2011]. (in Dutch).

Al-Homoud, M.S., 2005. Performance characteristics and practical applications of common building thermal insulation materials. *Building and environment*, Volume 40, Issue 3, pp. 353-366.

Aspen Aerogels, 2010. *Spaceloft Isolation Datenblatt.* [online] Aspen Aerogels. Available at: <www.aerogel.com/products/pdf/**Spaceloft**_DS_GERMAN.pdf > [Accessed: 25 October 2011]. (in German).

Aspen Aerogels, 2011. *Material safety datasheet Spaceloft.* [online] Aspen Aerogels. Available at:<http://www.aerogel.com/products/pdf/Spaceloft_MSDS.pdf> [Accessed: 25 October 2011].

Ballytherm, 2007. *Energy saving for the future: polyisocyanurate insulation board.* [online] Ballytherm. Available at: <http://www.ballytherm.ie/downloads/brochure.pdf> [Accessed: 4 October 2011].

Betonson, 2011. *EPS panels.* [online image] Available at: <http://www.betonson.com/_userfiles/07de1b36-c76c-4c0e-b7ff-c7b8daaca569/_userimages/platen-epS.jpg> [Accessed 3 October 2011].

Bio Home, 2011. *Prijs en materiaallijst Bio Home.* [online] Bio Home. Available at:<http://www.mediafire.com/file/vo6vewubkmcbnbr/materialenlijst_2011.pdf> [Accessed: 20 October 2011].

Bouwbesluit, 2003a. S1.4 (art. 1.6), [online] Available at :<http://vrom.bouwbesluit.com> [Accessed 12 October 2011] (in Dutch).

Bouwbesluit, 2003b. s5.1 (art. 5.3), [online] Available at :<http://vrom.bouwbesluit.com> [Accessed 30 August 2011]

Cobouw, 2011. *Glorieuze 'mislukking' BioFoam.* [online] Cobouw. Available at: <http://www.biofoam.nl/uploads/Artikel%20Cobouw%202011-09-12.pdf> [Accessed: 22 October 2011]. (in Dutch).

Concept Bouwbesluit 2012, 2011. s5.1 (art. 5.1), [online] Available at: <http://www.rijksoverheid.nl/bestanden/documenten-en-publicaties/besluiten/2011/05/02/ontwerpbesluit-bouwbesluit-2012/concept-bouwbesluit-2012.pdf> [Accessed 30 August 2011]

Bouwcenter, 2007. Isolatie. In: Bouwcenter, ed 2007. *Algemene productinformatie.* [online] Available at: <http://www.bouwcenter.eyefi.nl/pdf/Hoofdstuk_05_36.pdf> [Accessed: 27 September 2011]. (in Dutch)

Br-architect, 2010. *Injection of UF-foam into cavity wall.* [online image] Available at: <http://foto.pmg.be/EBR/EBR0212N01_v1F112B5C_groot.jpg> [Accessed: 4 October 2011].

Calsitherm, 2010. *Calsitherm Klimaplatte: Technische grondslagen*. [online] Calsitherm. Available at: <http://www.calsitherm.nl/files/2010/10/Folder_klimaplaten.pdf> [Accessed: 27 September 2011]. (in Dutch)

D-isolatie, 2010. *Aminotherm.* [online] D-isolatie. Available at: < http://d-isolatie.be/isolatie/media/download_gallery/disolatie_folder_print.pdf> [Accessed: 13 October 2011]. (in Dutch).

Deschacht Plastics, 2011a. *Prijslijst Recticel.* [online] Deschacht Plastics. Available at: <http://www.deschachtplastics.be/pdf.aspx?slang=NL&grp=DEQABGSA> [Accessed: 18 October 2011]. (in Dutch).

Deschacht Plastics, 2011b. *Prijslijst Enertherm Isolatie*. [online] Deschacht Plastics. Available at: <http://www.deschachtplastics.be/pdf.aspx?slang=NL&grp=DECBKCHZ> [Accessed: 19 October 2011]. (in Dutch).

Doscha, 2011. *Doschawol, informatie algemeen*. [online] Doscha. Available at: <http://www.eco-logisch.nl/pdfupload/Doschawol_informatie_algemeen.pdf> [Accessed: 5 October 2011]

Dow, 2009. *Dow – Oplossingen voor de Bouw.* [online] Dow. Available at: <http://www.blauwplaat.nl/Documentatie%20Styrofoam%20isolatieoplossingen.pdf> [Accessed 3 October 2011] (in Dutch).

Ecobouwen, 2011. *Flax wool panel.* [image online] Available at: <http://www.ecobouwen.nl/sites/default/files/imagecache/product/isovlas%20PL.jpg> [Accessed 4 October 2011].

Ecologisch, 2011. *Prijs Metisse MT+.* [online] Available at: <http://www.eco-logisch.nl/Metisse-Metisse-isolatie-platen-3761> [Accessed: 26 October 2011]. (in Dutch).

European flame retardant association (EFRA), 2006. *Flame retardant fact sheet: Halogenated Phosphate esters.* [online] EFRA. Available at: <http://www.cefic-efra.com/content/Default.asp?PageID=163> [Accessed: 8 November 2011]

Foamglas, 2010. *Prijslijst Foamglas 2010.* Nieuwegein: Foamglas. (in Dutch).

Foamglas, 2011. *Thermal insulation systems for the entire building envelope.* [online] Foamglas. Available at: <http://www.foamglas.ae/__/frontend/handler/document.php?id=890&type=42> [Accessed: 27 September 2011].

Groene bouwmaterialen, 2011. *Prijzen Doscha DB schapenwol isolatie.* [online] Available at:<http://www.groenebouwmaterialen.nl/c-1087080/doscha-db-schapenwol-isolatie/> [Accessed: 20 October 2011]. (in Dutch).

Hasselaar, B.L.H., 2004. *Vernieuwbare isolatie als duurzaam alternatief: een onderzoek naar de prestaties van vernieuwbare isolatiematerialen*. MSc thesis. Delft University of Technology. (in Dutch).

Hock, 2009. *Thermo Hemp, insulate and feel well.* [online] Available at: <http://www.thermo-hanf.de/cms/upload/pdf/Englisch/TH_prospekt_engl.pdf> [Accessed: 5 October 2011].

Hock, 2011. *Producte + Preise 2011.* [online] Hock. Available at: <http://www.steico.com/nc/download.html?cid=455&did=564&sechash=24e2fe31> [Accessed: 19 October 2011]. (in German).

Holzhey, L. *Type of fibres and their influence on the waste phase for hemp wool.* [e-mail] (Personal communication, 19 October 2011).

Homatherm, 2010. *Productvielfalt senkt Dämmkosten: Intelligent dämmen mit HOMATHERM.* [online] Homatherm. Available at: <http://www.homatherm.com/fileadmin/user_upload/service/presse/pressetexte/daemmen_rund_ums_haus/HOMATHERM_Sortiment.pdf> [Accessed: 4 October 2011]. (in German)

Homatherm, 2011a. *Productdatenblatt flexCL.* [online] Homatherm. Available at: <http://www.homatherm.com/fileadmin/media/downloads/service/pdb/PDB_flexcl.pdf> [Accessed 5 October 2011]. (in German).

Homatherm, 2011b. *Preisliste 2011 Für den Fachhandel.* [online] Homatherm. Available at:<http://www.homatherm.com/fileadmin/user_upload/service/de/PL_DE_Juni2011.pdf> [Accessed: 19 October 2011]. (in German).

Innodämm, 2011 *Spaceloft-Aerogelmatten Datenblatt.* [online] Innodämm. Available at: <http://www.innodaemm.de/download/daemmstoffe/Spaceloft-Aerogelmatten.pdf> [Accessed: 25 October 2011]. (in German).

Innodämm, 2011. *Aerogel-Granulat Datenblatt.* [online] Innodämm. Available at: <http://www.innodaemm.de/download/daemmstoffe/Nanogel-Granulat.pdf> [Accessed: 25 October 2011]. (in German).

Institut Bauen und Umwelt (IBU), 2008. *EPD: Unkaschierte bzw. unbeschichtete kunstharzgebundene Steinwolle-Dämmstoffe.* [online] IBU Available at:<http://bau-umwelt.de/download/CY7e391a58X122ca87db45X30b3/IBU_EPD_DRW_2008112_D.pdf> [Accessed: 16 December 2012]. (in German).

Isobouw, 2011a. *Leveringsprogramma en prijslijst september 2011.* [online] Isobouw. Available at: < http://www.isobouw.nl/brochure/prijslijst_nl/files/assets/downloads/files/Isobouw_prijslijst.pdf> [Accessed: 18 October 2011]. (in Dutch).

Isobouw, 2011b. *Biofoam information brochure.* [online] Isobouw. Available at: <http://realpages-v2.nexwork.nl/product.aspx?productid=deca6dc7-92ef-4a2b-9a96-47ad36405f8c> [Accessed: 21 October 2011].

Isover, 2008. *Renovatie en na-isolatie.* [online] Isover. Available at: <http://www.isover.nl/documentatieservice/themabrochures/renovatie-en-na-isolatie/brochure-renovatie-en-na-isolatie.pdf> [Accessed: 14 October 2011].

Isover, 2009. *Planet, people, prosperity: Our commitment to sustainable construction.* [online] Isover. Available at <http://www.isover.com/var/isover_com/storage/original/application/6d29ea576da2cf4586c77bf4be26d473.pdf> [Accessed: 26 September 2011].

Isover, 2010. *Glass wool panels.* [online image] Available at: <http://www.isover.be/UserFiles/Image/photo/Multimax%2030.jpg.jpg> [Accessed: 26 September 2011].

Isover, 2011. *Isover prijscatalogus.* [online] Isover. Available at: <http://www.isover.nl/documentatieservice/prijscatalogus-en-voorwaarden/prijscatalogus-2011/prijscatalogus-2011.pdf> [Accessed: 18 October 2011].

Isovlas, 2010. *Brochure bouwisolatie.* [online] Isovlas. Available at: <http://www.isovlas.nl/ps_image/website/Brochure_bouwisolatie.pdf> [Accessed 4 October 2011]. (in Dutch).

Isovlas, 2011. *Assortimentsoverzicht Brutoprijslijst Isovlas PN.*[online] Isovlas. Available at: <http://www.isovlas.nl/ps_image/website/prijslijst_pag3.pdf> [Accessed: 19 October 2011].

Institut Wohnen und Umwelt, 2009. *Bauen für die Zukunft.* [online] Dr. Rainer Greiff. Available at:<http://www.iwu.de/fileadmin/user_upload/dateien/wohnen/IWU_Greiff_Daemmstoffe_090708.pdf> [Accessed: 8 November 2011].

Jelle, B.P., 2011. Traditional, State-of-the-art and future thermal building insulation materials and solutions – Properties, requirements and possibilities. *Energy and buildings*, Volume 43, Issue 10, pp. 2549 – 2563.

Johns Manville, 2010. *Material Safety Datasheet Fresco Roof Insulation.* [online] Johns Manville. Available at: <http://msds.jm.com/irj/go/km/docs/documents/Public/MSDS/200000000097_REG_NA_EN.pdf> [Accessed: 29 September 2011].

Kemisol, 2004. *Technische documentatie: geëxpandeerd polystyreen.* [online] Kemisol Available at: <www.kemisol.be/pdf/techdoc%20ALL%20nl.pdf> [Accessed: 3 October 2011]. (in Dutch)

Kingspan, 2009. *Komo productcertificaat*. [online] Intron/Komo. Available at: <http://www.insulation.kingspan.com/nederland/pdf/komo_kooltherm_k15.pdf> [Accessed: 13 October 2011].

Kingspan, 2011. *Prijs en assortimentslijst*. [online] Kingspan. Available at: <http://www.ecotherm.nl/download.aspx?File=53> [Accessed: 19 October 2011].

Knauf, 2008. *Polyfoam Gamma.* [online] Knauf. Available at: <http://www.knaufinsulation.be/files/ki_be/upload/documents/Knauf_guide_isolation-Polyfoam_NL%20(triptyque)_2.pdf> [Accessed: 13 October 2011].

Knauf, 2011. *Knauf Insulation: Bruto adviesprijzen.* [online] Knauf. Available at: <www.plafondwinkel.nl/document&id=1636> [Accessed: 18 October 2011].

Kowatsch, S., 2010. Mineral wool insulation binders. In: L. Pilato, ed. 2010. *Phenolic Resins: A Century of Progress.* Heidelberg: Springer. Ch. 10.

Kuhnen, F., 2011. *Calcium silicate panels*. [image online] Available at: <http://www.kuhnhen.de/cms/upload/bilder/waermedaemmung_innen_01.gif> [Accessed: 27 September 2011].

LouRius, 2010. *Produktblatt Nanogele.* [online] LouRius. Available at: <http://www.lourius.de/pdf/produkte/TD_Nanogel.pdf> [Accessed 25 October 2011]. (in German).

Meeusen, J., 2006. *Na-isolatie van spouwmuren.* M.Sc. University of Gent. (in Dutch).

NaturBauHof, 2011. *Preislite perlite.* [online] NaturBauHof. Available at:<http://www.naturbauhof.de/lad_daemm_perlite.php> [Accessed: 27 October 2011]. (in German).

Nature of the game, 2011. *Removing the bark from a cork oak.* [image online] Available at: <http://1.bp.blogspot.com/-J9gg_tmsfFQ/TguAo2-w_6I/AAAAAAAAAx4/Fp2bY03vxXg/s1600/collecting-cork.jpg> [Accessed 6 October 2011].

Nederlands Normalisatie Instituut (NEN), 2001. *NEN-1068(NL) Thermische Isolatie van gebouwen – Rekenmethoden.* Delft: NEN. (in Dutch).

NVM, 2004. *Vermiculite, brandwerend isolatiemateriaal*. [online] NVM. Available at: <www.nvmproducts.nl/download/nvm_products_vermiculite.pdf> [Accessed 27 September 2011].

Papadopoulos, A.M., 2005, State of the art in thermal insulation materials and aims for future developments. *Energy and Bulidings*, Volume 37, Issue 1, pp. 77-86.

Passiefhuismarkt, 2011. *Rockwool panels*. [image online] Available at: <http://www.passiefhuismarkt.be/custom/page_content/221_large.jpg> [Accessed: 26 September 2011].

Pavatex, 2011a. *Achtergrondinformatie over de productie van PAVATEX-houtvezelisolatieplaten.* [online] Available at: <http://www.pavatex.nl/herstellung.aspx> [Accessed: 5 October 2011].

Pavatex, 2011b. *Bauhandbuch.* [online] Pavatex. Available at: <http://www.pavatex.de/downloads.aspx> [Accessed 5 October 2011]. (in German).

Pavatex, 2011c. *Preisliste Pavatex.* [online] Pavatex. Available at: <http://www.pavatex.de/downloads.aspx> [Accessed: 20 October 2011].

Proklima, 2009. *Natural foam blowing agents – Sustainable Ozone- and climate-friendly alternatives to HCFC s*. [online] Proklima. Available at: <http://www.gtz.de/de/dokumente/gtz2009-en-proklima-nat-blow-agents.pdf> [Accessed: 3 October 2011].

Ravago, 2011a. *Prijslijst DOW Styrofoam – Type A.* [online] Ravago. Available at: <http://www.ravago.be/pdf/Tarief%2029%20DOW%20STYROFOAM%2026032011.pdf> [Accessed: 18 October 2011]. (in Dutch).

Ravago, 2011b. *Prijslijst Xtratherm.* [online] Ravago. Availlable at: <http://www.ravago.be/pdf/Tarief%2028%20XTRATHERM%2005092011.pdf> [Accessed: 19 October 2011]. (in Dutch).

Recticel, 2011a. *Technical datasheet Eurothane Bi-3.* [online] Recticel. Available at: <http://www.recticelinsulation.co.uk/sites/default/files/inline-images/PDFTF_engels/TFEngl_EurothBi3.pdf?phpMyAdmin=aw69yuPqHirH2pCpOdcT18077ie> [Accessed: 3 October 2011].

Recticel, 2011b. *Technische fiche Powerroof.* [online] Recticel. Available at:<http://www.recticelinsulation.be/sites/default/files/inline-images/PDFTF_nederlands/versie_0311/Hfdst%2002_B%20Powerroof.pdf> [Accessed: 13 October 2011].

Rentier et al., 2005. *Jellema Bouwtechniek 4B Omhulling – Gevels.* 2nd ed. Utrecht/Zupthen: ThiemeMeulenhoff. (in Dutch).

Reppel, 2005. *Perlite isolatiekorrels*. [online] Reppel. Available at: <www.nvmproducts.nl/download/nvm_products_vermiculite.pdf> [Accessed 27 September 2011]. (in Dutch)

Reppel, 2008. *Siliperl: korrelisolatie voor spoumuren.* [online] Reppel. Available at: <static.nbd-online.nl/attachments/siliperl.pdf> [Accessed: 29 September 2011]. (in Dutch)

Sattler, 2006. *NASA's Aerogel: ook toepassingen op aarde!* [online] Available at:<http://www.twanetwerk.nl/default.ashx?DocumentId=5883> [Accessed: 25 October 2011].

Sheep Wool Insulation Ltd, 2011. *Production process of sheep wool insulation*. [online] Available at: <http://www.sheepwoolinsulation.ie/about/production_process.asp> [Accessed: 5 October 2011]

Simmler, H., Brunner, S., 2005. Vacuum insulating panels for building application: basic properties, aging mechanisms and service life. *Energy and buildings*, Volume 73, Issue 11, pp. 1122 – 1131.

Spierings et al., 2004. *Jellema Bouwtechniek 03 Draagstructuur.* 2nd ed. Utrecht/Zupthen: ThiemeMeulenhoff, p128. (in Dutch)

Stybenex, 2007. *Basisinformatie EPS, eigenschappen en gegevens.* [online] Stybenex. Available at: <http://www.stybenex.nl/basisinformatie/bcc6847c/1/basisinformatie.aspx> [Accessed: 10 October 2011]. (in Dutch).

Staatscourant, 2005. *Wijziging regeling bouwbesluit 2003.* Year 2005, edition 163. [online] Available at: <https://zoek.officielebekendmakingen.nl/stcrt-2005-163-p10-SC70834.pdf> [Accessed: 13 October 2011].

Steico, 2011. *Preisliste / Lieferprogramm 2011.* [online] Steico. Available at: <http://www.thermo-hanf.de/cms/upload/pdf/prospekte/Preisliste_deutsch.pdf> [Accessed: 19 October 2011]. (in German).

Synbra, 2011a. *Energy Requirements and CO_2 emissions for polymers.* [online] Available at: <http://www.biofoam.nl/index.php?page=testje&language=> [Accessed: 22 October 2011].

Synbra, 2011b. Physical and thermal properties. [online] Available at: <http://www.biofoam.nl/index.php?page=testje&language=> [Accessed: 22 October 2011].

Technisol, 2005. *Technisch informatieblad pur'fect polyurethaan schuimen*. [online] Technisol supplies. Available at: <http://www.technisol.nl/PDF/technische_informatie_polyurethaan_platen.pdf> [Accessed 3 October 2011]

Thermecon, 2007. *Thermische isolatiematerialen voor buitenwanden.* [online] NBD Available at: <http://www.nbd-online.nl/module/pdf_nbd_2006/9397_01_Dancowol%20minerale%20inblaaswol%20voor%20spouwmuurisolatie.pdf> [Accessed 4 October 2011]. (in Dutch).

Tonzon, 2008. *Wandisolatie met thermosheets.* [online] Tonzon. Available at:<http://www.tonzon.nl/index.php?page_id=298&task=download&path=Productinformatie%2Fwandisolatie.pdf> [Accessed: 27 October 2011]. (in Dutch).

Tonzon, 2011a. *Thermocushions under concrete floor.* [online image] Available at: <http://www.tonzon.nl/wp-content/gallery/vloeren-beton/kruipruimte.jpg> [Accessed 4 October 2011].

Tonzon, 2011b. *Montage vloerisolatie.* [online] Available at: <http://www.tonzon.nl/vloer-en-bodem-isoleren/montage-vloerisolatie/montage/> [Accessed: 10 October 2011]. (in Dutch).

Tschopp, 2010. *Aerogel Spaceloft Hochleistungsdämmstoff.* [online] Tschopp. Available at: <http://www.tschoppbasel.ch/tscho_09/aktuell.htm> [Accessed: 25 October 2011]. (in German).

Unilin, 2011. *Prijslijst Utherm isolatieplaten.* [online] Unilin. Available at: <http://www.unilininsulation.com/nl/downloads/PDF/Prijslijst%20Utherm%20Augustus%202011.pdf> [Accessed: 19 October 2011]. (in Dutch).

Unser Bausatzhaus, 2009. *Aerogel® / Nanogel Hochleistungsdämmstoff (Granulat).* [online] Unser Bausatzhaus, 2009. Available at: <http://unser-bausatz-haus.de/index2.php?option=com_content&do_pdf=1&id=58> [Accessed: 25 October 2011].

Vac-Q-Tec, 2011. *Va-q-vip B product data sheet.* [online] Vac-Q-Tec. Available at:<http://www.va-q-tec.com/download_produkt.php?system_id=3348&com=liste&src=produkte%2Fen%2Fpvipb%2Fprod%2Fva-q-vip_b_pdb_en.pdf> [Accessed: 07 November 2011].

Van Avermaet, 2011a. *Coconut panels.* [image online] Available at: <http://www.vanavermaet.be/images/producten/groot/Coco1.jpg> [Accessed 10 October 2011].

Van Avermaet, 2011b. *Kokosmatten.* [online] Van Avermaet, 2011b. Available at: <http://www.vanavermaet.be/pdf/CocosisolatieplatenNED.pdf> [Accessed: 10 October 2011] (in Dutch).

Van Avermaet, 2011c. *Geëxpandeerde kurkplaten en korrels.* [online] Van Avermaet. Available at:< http://www.vanavermaet.be/pdf/KurkplatenKorrelsNED.pdf> [Accessed 6 October 2011]. (in Dutch).

Van den Hout A.F. et al., 2005. *Jellema Bouwtechniek 4A Omhulling – Prestatie-eisen/daken.* 2nd ed. Utrecht/Zupthen: ThiemeMeulenhoff. (in Dutch).

Vijfwinkel, 2011. *Information on cavity wall insulation with Homatherm products* [phone call] (Personal communication, 26 October 2011).

Vlaams Instituut voor bio-ecologisch bouwen en wonen (VIBE), 2007. *Technische keuzefiches: Isolatiematerialen*. [online] VIBE. Available at: <http://www.vibe.be/downloads/1.Technische_documentatie/Bouwmaterialen%20en%20gezondheid/KF_isolatiematerialen.pdf> [Accessed 21 September 2011]. (in Dutch).

VRK isolatie, 2011. *Catalogus Metisse.* [online] VRK isolatie. Available at: <http://www.isolatiemetisse.nl/images/stories/catalogus%202011%203mb.pdf> [Accessed: 26 October 2011]. (in Dutch).

Wecobis, 2011. *Polyurethan-Hartschaum (PUR/PIR).* [online] Wecobis. Available at: <http://www.wecobis.de/jahia/Jahia/Home/Bauproduktgruppen/Daemmstoffe/aus_synthetischen_Rohstoffen/Polyurethan-Hartschaum> [Accessed: 8 November 2011].

Willemsen, T., 2011. *Fire classification of Tonzon foils.* [e-mail]. (personal communication, 18 October 2011]. (in Dutch).