1.4. Thermal insulation materials

1.4.1. General overview

The overall of the project is to contribute to the enforcement of the requirements of Directive 2012/27/ EU of the European Parliament, more specifically to develop complex solutions based on the smart materials, innovative technologies and renewable resources for the nearly zero energy buildings (nZEB), as according to directive an economically justifiable mass construction with regard to nZEB should be started in 2019.

In the scope of insulation materials the aim is to develop know-how concerning an energy efficient and sustainable construction under the temperate climatic conditions and to find effective and functional thermal insulation materials (for example, aerogel or vacuum insulation panels) and easy, convenient and quality assured mechanical integration technology (wooden and granular materials), taking in account economic justification of such solutions.

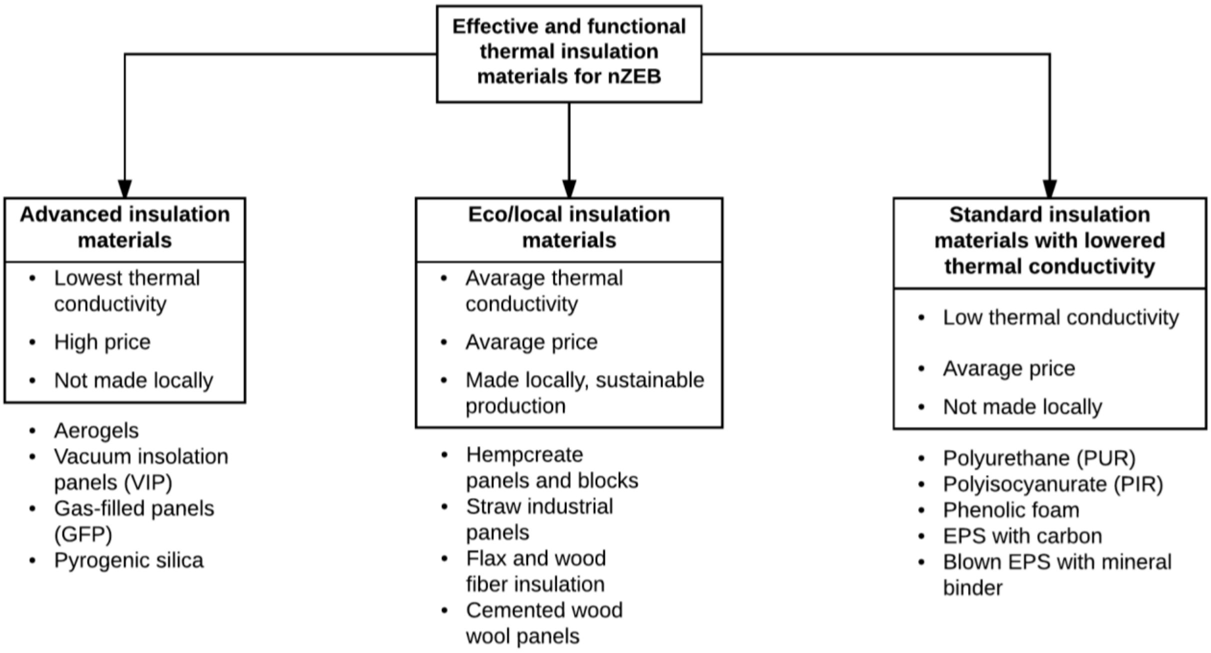

Figure 1.25. *Three major groups of effective insulation materials reviewed in summary*

To achieve the aims and objectives of this project all thermal insulation materials can be divided in three groups (Figure 1.25): Advanced insulation materials, Eco/local insulation materials and Standard insulation materials with lowered thermal conductivity.

Group of Advanced insulation materials includes materials which have been commercially available only in recent years, can achieve significantly low thermal conductivity and can be considered State-of-art solutions. Because of the aforementioned reasons these materials also have notably high price when compared to other insulation materials, also none of them are made locally. This material group includes Aerogels, Vacuum insulation panels (VIP), Gas-filled panels (GFP) and pyrogenic silica.

Eco/local insulation materials can be include in the second group reviewed in this summary (Figure 1.25.). These generally consist of bio-based material that is either and agricultural or wooden by-product with or without mineral binder. All these materials are or can be made locally as the raw materials or their production technologies are readily available. One large advantage of such materials are their ecological properties, both in terms of production and exploitation (for example, indoor air quality, moisture and etc.). This group includes but is not limited to: Hempcrete panels and blocks, Straw industrial panels, Flax and wood fiber insulation, Cemented wood wool panels etc.

The third group consists of materials that are being used in construction industry to some extent, but their price or relatively recent introduction have led to limited usage. All these materials have lower thermal conductivity then traditional ones that make them very appropriate choice for nZEB. Materials from this group almost entirely consists of materials of organic origin made by chemical synthesis, such as Polyurethane, Polyisocyanurate, Phenolic foam, Expanded polystyrene with graphene additives and others.

All of the groups have their own advantages and disadvantages, mainly concerning thermal conductivity, price, local production and environmental impact, which will be summarized in later chapters.

1.4.2. Advanced insulation materials

Today's architectural vanguard demands a building system such as is proposed in this research: a lightweight, variable geometry, seamless high energy performance system that also permits the passage of natural light and backlighting. No system combing all these features exists as yet, and similar systems are not absolutely free form and translucent, are not seamless and/or have a very limited thermal (Almusaed, 2012).

In recent years, a great deal of effort has been dedicated to developing new technological solutions with the aim of reducing the heating and cooling energy consumption of buildings. One of the most promising solutions for the construction sector is the use of super insulation materials, such as vacuum insulation panels (VIPs) and Areogel-containing materials, in building envelope components. They allow optimal thermal insulation levels to be achieved, while keeping the total thickness of the envelope components below a certain thickness. Nevertheless, some barriers have to be overcome in order to penetrate the building construction market and to be widely adopted by designers. In fact, although these materials show remarkable potential for reducing energy consumption, few investigations have been carried out so far to evaluate their effectiveness in real building applications. In particular, the effects of the configuration adopted for their installation, in terms of design and materials, and the procedures used to evaluate their overall performance need to be investigated in more detail.

The use of vacuum insulation panel (VIP) systems in building aims to minimize the thickness of the building's outer skin while optimizing energy performance. The three types of vacuum chamber insulation systems (VIS) most commonly used in the construction industry today –metallized polymer multilayer film (MLF) or aluminium laminated film, double glazing and stainless steel sheet or plate (W. Willems, 2006). All these materials have weaknesses, such as the fragility of the outside protective skin, condensation inside the chamber, thermal bridges at the panel joints, and high cost, all of which have a bearing on on-site construction (Baetens et al., 2010). Apart from overcoming these weaknesses and being a transparent system, the new FTE (free-form, transparent, energy efficient envelope) system that we propose has two added values. The first is the possibility of generating a structural skin or self-supporting façade. The second is the possibility of designing free-form architectural skins.

From the viewpoint of energy performance, of the three types of translucent insulations that there are on the market (plastic fibers, gas and aerogel), the insulation that meets the needs of the new system is aerogel (Ismail, Salinas, & Henriquez, 2008) (Ismail et al., 2008).

Aerogel and nanogel (granular silica gel) have four advantages for use as thermal insulation in translucent panels:

1. **Transparency:** aerogel is comparable to glass in terms of transparency (Moner-Girona et al., 2002). Monolithic aerogel light transparency can be as high as 87.6%, even greater than what some gas-insulated glasses can offer. Granular nanogel offers a greater translucency than any other traditional insulation material (including plastic fiber blankets).
2. **Insulation:** on top of transparency, it is an excellent insulator. According to published data (Baetens et al., 2010), the thermal performance of a 70 mm nanogel-filled VIP is better than a 270 mm-thick hollow wall. The insulation values of a 15 mm nanogel-filled polycarbonate sheet are higher than any double glazing of similar thickness.
3. **Lightness:** aerogel can be three times as heavy as air (Rubin & Lampert, 1983), which means that the panels that employ this material for insulation are very lightweight even though the density of the aerogel that we use as insulation is 50-150kg/m^3.
4. **Versatility:** monolithic aerogel can be shaped as required. Being a nano-sized filling, granular nanogel can be used to fill any chamber.

Most widespread system on the market is **nanogel-filled cellular polycarbonate panels**. They have the following strengths and weaknesses:

- **Strengths:** Thanks to its low density 1.2g/m^3, this is a very lightweight material. It has a high light transmission index ±90% (almost the transparency of methacrylate). It is a lowcost material for immediate use. And, at the competitiveness level, it is the least expensive envelope assembly.
- **Weaknesses:** Durability is low. Most commercial brands guarantee their polycarbonate panels for only 10 years (as of when they start to deteriorate), whereas nanogel has a very high durability. These panels are very lightweight but very fragile to impact. Even though nanogel is an excellent acoustical insulator, the slimness of these panels means that they have acoustic shortcomings.

No more than two types of **reinforced polyester panels** are commercialized despite the potential of this material. They have the following strengths and weaknesses:

- **Strengths:** Good mechanical properties: glass fiber reinforced polyester resin core composites offer excellent flexibility, compressibility and impact resistance. Good malleability: they could be shaped according to design needs but no existing system offers this option. Durability is good, as there are methods to lengthen the material’s service life considerably (twice that of polycarbonate), like gelcoat coatings or protective solutions with an outer layer composed of a flexible “glass blanket”.
- **Weaknesses:** There is no self-supporting (structural) panel that is standardized and commercialized worldwide. Existing systems have design faults, as they include internal aluminum carpentry or substructures, whereas there is, thanks to the characteristics of reinforced polyester, potential for manufacturing a self-supporting panel (as in the case of single-hull pleasure boats). It is also questionable ecologically, as the polyester is reinforced with glass fiber, which has detracted from its use in building. However, this could change with the advent of new plastic and organic fibers and resins. Economically speaking, reinforced

polyester manufacturing systems are very expensive, because either processes are not industrialized or, on the other hand, they rather technology intensive like, for example, pultrusion

Double glazed vacuum insulated panels (VIP) are still at the prototype stage. Although research and prototypes abound (HILIT+ y ZAE BAYERN, for example) (Fricke, 2005), there are only a couple of commercial brands:

- **Strengths:** Thanks to the combination of vacuum and aerogel insulation (both monolithic and granular), they provide the slimmest and best insulation system in the building world (0.5W/m²K). Transparency levels for some prototypes using monolithic aerogel are as high as 85% for thicknesses of 15 to 20 mm. Additionally, the service life of the glazing and the gel is very similar.
- **Weaknesses:** Product of a combination of vacuum core and double glazing, this component is fragile, especially prone to impact-induced breakages. The high cost of molding glass into complex geometries rules out its use as a free form system. It is a system that depends on substructures and other components for use.

As regards energy efficiency, these products offer more energy-saving performance than a 27cm thick traditional wall. With only 7 cm, they have an U value of 0.28W/m²K, which amounts to 7% better energy performance compared to a traditional wall and with 4% less thickness. Looking at double glazed VIP panels; the data indicate that, although still at the prototype stage, panels like these are the best commercial solution, as they offer the best thermal and acoustical insulation performance and optimal light transmission.

At the acoustical and thermal level, the VIP panel is the best of the envelopes examined, as a 15 mm panel insulates equally as well as a traditional mass wall in terms of energy expenditure (saving). We find that, with a thickness of just 60 mm, this product improves the energy efficiency performance of a 271.5 mm cavity wall.

All panels implemented with aerogel instead of nanogel are transparent. They have a high solar transmittance and low U value. At present all these systems are non-commercial prototypes, about which little is known. Noteworthy are two aerogel-insulated doubleglazed vacuum insulation panels (VIP):

- double-glazed vacuum panels filled with monolithic aerogel with a pressure of 100hPa1 in the aerogel chamber. The heat transfer coefficient Ug has a U value of 0.7 W/m²K for 14 mm and 0.5 W/m²K for 20 mm compared to the 1.2W/m²K offered by 24 mm commercial nanogel-filled double glazing VIP. This almost doubles the insulation performance of the best commercial translucent panel. Light transmission depends on the angle of incidence, but varies from 64.7 to 87.5%. The sound attenuation index is 33dB for a panel thickness of 23 mm and noise reduction is expected to be improved to 37 dB. The energy saving compared with a dwelling that is glazed with gas-insulated triple glazing (argon and krypton) is from 10% to 20% greater.
- Double-glazed vacuum insulation panels with aerogel spacers inside the core (unlikely to be commercialized for another two or three years). The heat transfer coefficient Ug for 10 mm panels has a U value of 0.5 W/m²K. This is the best of all the panels studied so far, where light transmission is equal to glass.

1.4.3. Selected advanced insulation materials

In general aerogel is a porous material similar to gel, where only the solid framework is left – the liquid part is replaced by gas. The material has extremely low densities, at which very low thermal conductivity can be achieved. Aerogels can be made of many different materials. The name only refers to geometry of their arrangement. Most aerogels used for building applications are made of silica.

Regarding building applications aerogels can be split in two groups, based on their transparency. The first group is partly transparent aerogel products and their main use is in enhancing window thermal conductivity and in the same time allowing for the light to go through. The other group is opaque aerogel materials, rigid or flexible, for enhancing thermal properties of walls, ceilings and floors.

Transparent aerogels

Cabot "Lumira" aerogel

"Cabot" is one of the leading specialty chemicals and performance materials production company. Their "Lumira" aerogel is most widely used particulate silica aerogel that is used for daylight applications. As it is in bulk form, it is used as filling material of glass sandwich panels, sky roofs, window panels and various other transparent building elements.

"Lumira" aerogel has particle size range of 0.7-4.0 mm, pore diameter of around 20 nm, porosity greater than 90%, particle density of 120-150 kg/m^3, bulk density 65-85 kg/m^3, hydrophobic surface, light transmission of 90% per cm of thickness, thermal conductivity 0.018 W/m*K at density of 85 kg/m^3 and 0.023 W/m*K at 65 kg/m^3 (Figure 1.26.).

"Lumira" is used by many different companies to create various daylight solutions – structural polycarbonate systems (Advanced Glazings, Ltd, Alcaud S.A., Solar Innovations, Wasco and others), custom tensile membrane structure (Birdair), U-channel glass (Pilkington BGI, Technical Glass Products) and structural composite panels (Kalwall, Solera)[1]. The last group is particularly interesting in the scope of nZEB, as it is possible to replace some of the higher U-Value traditional windows with these low U-Value daylights with aerogel insulation.

Figure 1.26. *Cabot "Lumira" aerogel L1000 particles*[2]

[1] http://www.cabotcorp.com/solutions/applications/construction/daylighting/daylighting-partners
[2] http://www.cabotcorp.com/solutions/applications/construction/daylighting/daylighting-partners

Solera "Lumira" aerogel panels

Solera specializes in daylighting solutions providing deep penetration of sunlight indoors, by using wide angle diffusing translucent glass, thus lifting a significant portion of the sunlight from the floor and distributing it more evenly throughout the room (Figure 1.27.).

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Figure 1.27. *Joggins Fossil Cliff Museum with Solera "Lumira" panels in front façade*[1]

"Solera" panels can be filled their own "InsolCore" transparent insulation that uses rigid fiberglass insulation. This insulation can be replaced by "Lumira" aerogel thus lowering U-Value three times to 0.31 W/m^2*K (Table 1.4.)[3].

Kalwall "Lumira" aerogel panels

Kalwall specializes in light-transmitting, structural sandwich panel production. Their produced panels can be used as facades, curtain walls, window replacements, as well as sky roofs, skylights and canopies (Figure 1.28.).

Figure 1.28. *Kalwall "Lumira" aerogel panels Canada Street, Auckland*[4,5]

[3] http://www.cabotcorp.com/solutions/applications/construction/daylighting/daylighting-partners
[4] https://www.kalwall.com/technology/panel-anatomy/translucent-insulation/

Similar to "Solera", for standard solutions low thermal conductivity is achieved with transparent fiberglass insulation. This thermal insulation can be enhanced, by using "Lumira" aerogel and achieving U-Values of 0.28 W/m^2*K for 70 mm thickness panel (Table1.4.)[6].

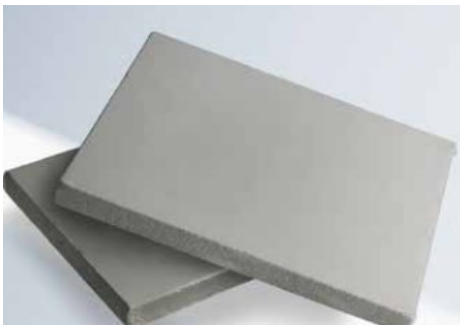
Table 1.4. *Properties of panels that use Lumira aerogel*

	SOLERA + Lumira aerogel R18	Kalwall + Lumira 70 mm panel
Nominal thickness	76.2 mm	70 mm
Visual Light Transmittance (VLT)	7% - 32%	20%
Shading Coefficient (SC)	0.08 - 0.36	0.287
Solar Heat Gain Coefficient (SHGC)	0.07 - 0.30	0.25
U-Value	0.31 W/m^2·K	0.28 W/m^2·K
Sound Transmittance Class (STC)	may exceed 52	-

Non-transparent aerogels

"Evonik Calostat"

"Evonik Calostat" is a rigid aerogel panel that is made from silicon dioxide (Figure 1.29). It has low thermal conductivity of 0.019 W/m*k and density of 165 kg/m^2. As silicon dioxide is the raw mineral material that "Calostat" is made of, the fire rating classification according to EN 13501 is A2-s1, d0, which means it is nonflammable. The material is also hydrophobic and has average compressive strength of > 90 kPa, it does not contain fungicides, algaecides or pesticides, does not react with other composite materials, resistant to mold growth and recyclable (Table 1.5.)[7].



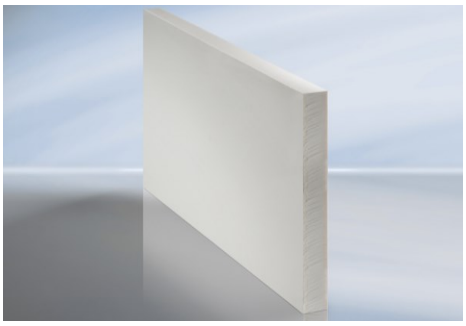


Figure 1.29. *"Evonik Calostat" panels - left[7] , BASF Slentite panel – right[8]*

[5] https://www.kalwall.com/kalwall-products/facades/walls/

[6] http://www.advancedglazings.com/wp-content/uploads/2017/06/Solera_English_2017_1.pdf

[7] http://www.calostat.com/sites/lists/RE/DocumentsSI/CALOSTAT-A-warming-idea-an-awesome-innovation-EN.pdf

BASF “Slentite”

BASF “Slentite” is rigid organic aerogel panel that is mechanically strong and made from polyurethane. With compressive strength of more than 300 kPa, it outperforms all other aerogel insulation materials (Table 1.5.). It can be handled like any other building insulation panel, it can be sawn, milled and drilled, and it is dust-free. Its open pores structure makes it appropriate choice as core for vacuum insulation panels (VIPs)[8].

“Fixit 222” aerogel plaster

“Fixit 222” aerogel plaster uses aerogel produced by Cabot and embeds it in a lime-cement plaster. With this combination it can achieve one of the lowest thermal conductivity coefficients that is achieved for commercial plaster 0.028 W/m*K (Table 1.5.). It can achieve the A2-s1, d0 class as it is mineral based and together with high water vapor permeability it makes it mould and mildew resistant[9].

Proctor “Spaceboard”, Active aerogels “Silflex”, “Thermablock” Aerogel insulation strip

Proctor “Spaceboard”[10], Active aerogels “Silflex”[11], “Thermablock Aerogel” insulation strip[12] – all of these ar flexible aerogel insulation mats. Although their thermal properties vary slightly (Table 1.5.), their general use is similar – as extra thermal insulation layer, allowing to use insulation from inside of the room, thus reducing the floor are lost to conventional insulation materials (Figure 1.30.). Also these materials can only achieve C-s1, d0 class, as their flexible base material is organic origin.

These materials are also said to be vapor permeable, hydrophobic and remains its thermal conductivity for over 50 years in case of Proctor “Spaceboard”. Flexible aerogel mats provide similar or even better insulation capabilities than rigid panels, thus making it more suitable for nZEB.

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[8] http://www.polyurethanes.basf.com/pu/solutions/en/function/conversions:/publish/content/group/ News _und_Medien/Polyurethan/Slentite_EN.pdf
[9] http://www.fixit.ch/aerogel/?w=daemmputz
[10] http://www.proctorgroup.com/images/downloads/Thermal-Insulation/Spacetherm/Spacetherm_ Building _Construction.pdf
[11] http://thermablok.com/thermal-insulation/technical-support.htm
[12] http://www.activeaerogels.com/flexible-panel/

Figure 1.30. *Flexible aerogel insulation – Proctor Spaceboard (left), Active aerogels Silflex (middle), Thermablock Aerogel insulation strip (right)*

Table 1.5. *Non-transparent aerogel properties*

Properties and testing methods	**Unit**	**Evonik CALOSTAT**	**BASF Slentite**	**FIXIT ag 222**	**Proctor Spaceboard**	**Thermablok**	**Silflex**
Type		Board	Board	Plaster	Mat	Strips	Mat
Bulk density	kg/m³	165	-	220	150	150	130
Thermal conductivity (λ)	W/(mk)	0.019	0.017	0.028	0.015	0.0131	0.025
Vapor diffusion resistance (μ)	(μ)	6	-	4-5		-	-
Water absorption	kg/m²	≤ 0.1	-	W1	-	-	-
Moisture absorption	M-%	≤ 1.0	-	-	-	1.08%	-
Compression strength	kPa	> 90	300	4000-25000 (CS I)	55	68	-
Elastic recovery / recovery reversible	%	≤ 10	-	-	≤ 10	≤ 10	-
Fire	-	A2-s1, d0	-	A2-s1, d0	C-s1, d0	C-s1, d0	-

1.4.4. Vacuum insulation panels (VIPs)

Vacuum insulation panels present superior thermal insulation properties, even greater than those of aerogels (Figure 1.31.). It is possible to achieve thermal conductivity coefficient in range of 0.002 – 0.006 W/m*K, that can be 7 time lower than that of aerogel insulation properties. Using vacuum insulation panels it is possible to save even more indoor are to insulation that is why traditionally VIPs have been used as insulation in vending machines and other applications connected to refrigeration industry.

Promat SlimVac, Isover IsoVIP, va-Q-tec va-Q-vip

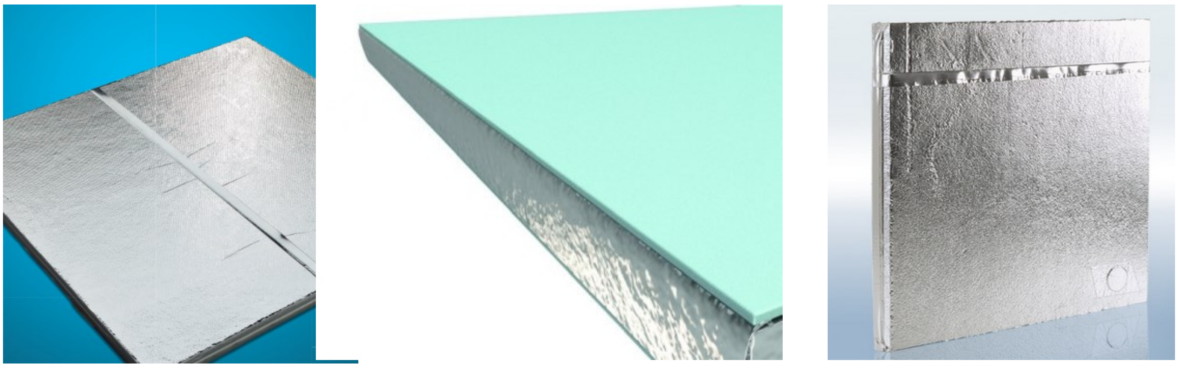

Figure 1.31. *VIPs – Promat SlimVac (left)[13], Isover IsoVIP (middle)[14] , va-Q-tec va-Q-vip (right)[15]*

The main disadvantage of VIPs lays in their fragile nature. Panels should be treated with extreme care during installation, as damaged panel assumes thermal conductivity of its inner core material, that can be aerogel, pyrogenic silica, fiberglass insulation or other insulation material with thermal conductivity of around 0.020 W/m*K. Extra care is necessary to also protect materials throughout their whole usage period. VIPs also lose some of their vacuum due to slow air infiltration, in 25 years thermal conductivity rises by around 0.003 W/m*K.

Promat SlimVac, Isover IsoVIP and va-Q-tec va-Q-vip are all similar VIPs, they have similar densities and thus thermal conductivity is similar around 0.005 – 0.006 W/m*K. From Figure 1.30. it can be seen that their overall execution is also similar – all of them consist of aluminum foil outer layer as pressure barrier. Only significant difference is the inner core material used, in case of SlimVac and va-Q-vip it is pyrogenic silica insulation, in case of IsoVIP it is polyurethane. Thus the difference is in reaction to fire. The first two are non-combustible, IsoVIP can only achieve F class. Summary of all Vacuum insulation panel properties can be seen in Table 1.6.

Table 1.6. *Vacuum insulation panel properties*

Properties and testing methods	Unit	Promat SlimVac[11]	Isover IsoVIP[12]	va-Q-vip [14]
Bulk density	kg/m^3	160-210	170-210	175-250
Thermal conductivity (λ)	W/(mk)	0.0061	0.0052	< 0.005
Temperature range	°C	- 50 to + 80	-	-70 to + 70
Moisture resistance	%	60	-	60
Reaction to fire	-	Non-combustible	F class	Non-combustible
Compressive strength	MPa	0.2	-	0.15

[13] http://www.promat-hpi.com/en/applications/buildings/building-outside/slimvac-terraces-roofs-walls-glass-facades
[14] https://www.isover.com/news/isovip-high-performance-vacuum-insulation-solution-isover-france
[15] https://www.isover.fr/sites/isover.fr/files/assets/documents/AT_Optima-VIP_20_15_360_021621F104134DBEACA546B8DF142665.pdf

Gas filled panels (GFPs)

Gas filed panels (GFPs) uses external aluminum foil and polymer laminates and internal aluminum film layers, to create a honeycomb structure when inflated full of air or other gas (Figure 1.32.). Fi-Foil is one of the biggest GFP suppliers, their GFP Insulation panel can achieve U-Values of thermal conductivity of 0.035 W/m*K with air, 0.021 W/m*K with argon and 0.010 W/m*K with krypton[16]. Advantage of these materials is their low thermal conductivity with low material usage, disadvantages are similar to VIPs – significantly difficult installation and use, as even little damage can destroy whole panel.

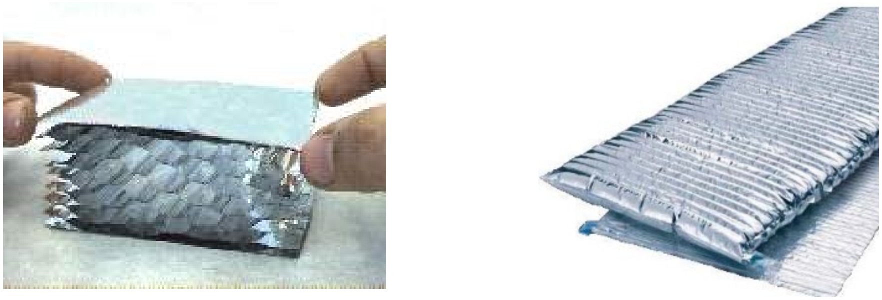

Figure 1.32. *Gas filled panels – inner structure (left)[16] [14], Fi-Foil GFP panel (right)[17]*

1.4.5. Ecological/local insulation materials

Ecological insulation materials made of local raw materials is the second big group of materials that will be review in this summary. All these materials share two common properties, they all contain agricultural or wooden particles (by-products and purposely grown) and they all are or can be produced locally, as the raw materials or technological production solutions is readily available. To some extent all materials in this group can be called ecological, as overall negative effect on environment or to the indoor quality is much less than that of traditional building materials.

The materials in this group includes rigid wooden frame agricultural waste panels as Hempcrete panels – hemp shives with binder and Ecococon straw panels – baled and pressed straw panels. It also includes cement-wood construction boards and various wool insulation – flax, wood and seaweed based insulation for example NeptuTherm. Also a hemp based lime plaster will be reviewed.

Hempcrete

One of the materials that have some gained popularity in recent years thanks to its ability to sequester CO_2 and to buffer indoor air moisture is Hempcrete. It is made of industrial by-product of hemp fiber production – hemp shives and lime based binder (LHC). It is used as self-bearing thermal insulation material usually with structural timber frame. To understand fully all positive properties of Hempcrete it is review here through CO2 the prism of EU

[16] http://www.va-q-tec.com/en/products/vacuum-insulation-panel-vip/va-q-vip.html
[17] http://www.colorado.edu/engineering/ASEN/asen5519/08incubator-heat.htm

regulation N305/2011 which sets 7 requirements for construction and building materials (Sinka, Sahmenko, & Korjakins, 2014):

1. Mechanical resistance and stability – it has much higher mechanical resistance as typical thermal insulation materials, as it does not need any extra layers with materials and a plaster can be applied straight on the surface (Elfordy, Lucas, Tancret, Scudeller, & Goudet, 2008)
2. Safety in a case of fire – the addition of mineral binders can improve hemp fire resistance up to class B by EN 13501-1 (Sassoni, Manzi, Motori, Montecchi, & Canti, 2014) compared to typical E class of natural fiber insulation materials without mineral binder (Kymäläinen & Sjöberg, 2008).
3. Hygiene, health and the environment – LHC does not contain VOC`s or any other harmful substances. It also has great moisture buffering capabilities, which improves indoor air quality by preventing fungus and mould growth – which is a cause for allergic diseases (Tran Le, Maalouf, Mai, Wurtz, & Collet, 2010), (Ó Broin, Mata, Göransson, & Johnsson, 2013).
4. Safety and accessibility in use – no major advantages/disadvantages.
5. Protection against noise – due to its porous and fiber structure, higher density than regular insulation materials, LHC insulates sound with both absorption and reflection providing better sound insulation at equal thickness (Cerezo Véronique, 2005).
6. Energy economy and heat retention – LHC has a relatively good thermal insulation properties – λ below 0.080 (W/m*K) which makes it compatible with other insulation materials (Sassoni et al., 2014), (Benfratello et al., 2013).
7. Sustainable use of natural resources – it has been proven by several researchers that the whole manufacture process of LHC sequester more CO_2 then is released into the atmosphere, as the hemp plant takes up carbon dioxide in growing process and lime also gathers CO_2 in its hardening process. The amount of carbon dioxide sequestered is around 35 kg for 260 (Ip & Miller, 2012) or 300 (Shea, Lawrence, & Walker, 2012) mm thick LHC wall.

As not all of the properties are declared by the producers, it is necessary to summarize general properties of this material from available scientific literature. In scope of this project local producers of ecological materials are more interesting. Currently there are two companies producing Hempcrete products in Latvia – “Hemp Eco System Latvia” Ltd. and “Esco Būve” Ltd. that is most known for their trademark “Remember Brothers”.

“Hemp Eco System Latvia” Ltd has been approbating the production technology from the Swiss company “Hemp eco systems SA”. Company mix the Hempcrete concrete on site and pour it in the shuttering system. This method although good for individual design of houses does present challenges, the main being high labor intensity. It would be under question to significantly increase popularity of such as materials produced by this method in the sector of nZEB, thus this method is dismissed in favour of more industrialized approach.

The company “Remember Brothers” is using more industrialized approach producing their panels in factory and only assembling them on site (Figure 1.33.) compare with “Hemp

Eco System Latvia" Ltd. This allows for much less labor intensive construction and also makes the whole construction cycle more independent from weather conditions. The company is using hemp shives from local producers as raw material, thus most of the material is entirely made locally. The binder is specially produced by the local dry mixture producer "Sakert" Ltd., although using also imported raw materials as for example hydraulic lime is not produced locally, but is essential for the mixture. The declared properties of the material can be seen in Table 1.7.

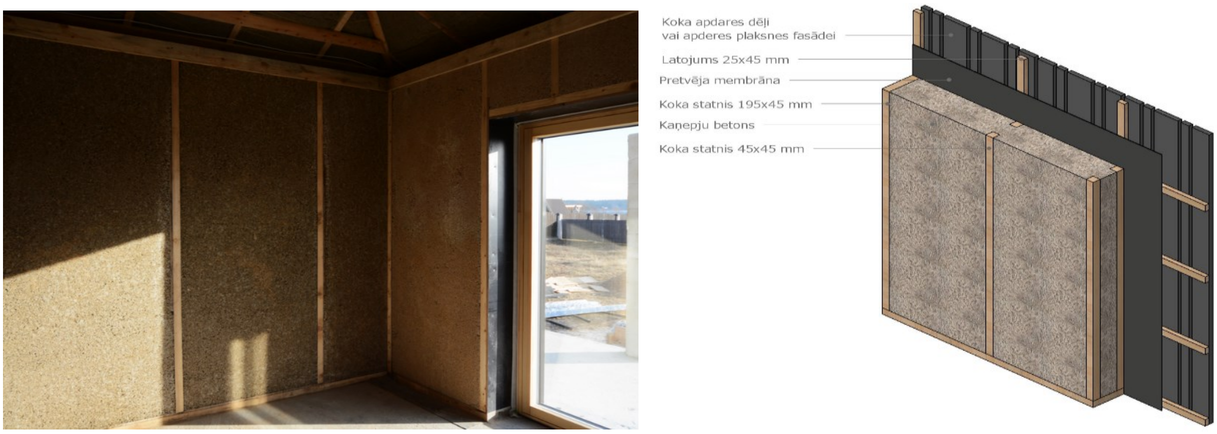

Figure 1.33. "*Remember Brothers" Hempcrete panels*[18]

"Ecococon" straw panels

For production of "Ecococon" straw panels similar technology as it was descripted previously regarding with hemp panels is used (Figure 1.34.). Structural timber frame is used in combination with agricultural by-products –straw, only in this case no mineral binder is used. Straws are dried (moisture level not exceeds 15%) and compressed to achieve density 100-120 kg/m^3 thus achieving more uniform straw directional alignment which increases thermal conductivity. These panels are also easy to install on site, thus allowing this solution to be used on wide scale. the panel can achieve fire rating class of B—s1,d0 (Tab.1.4.) by plaster applying[19].

Figure 1.34. *Ecococon straw panels*[19]

[18] http://www.rememberbrothers.com/galerijas
[19] http://www.ecococon.lt/latvia/downloads/vispariga-informacija/

Cewood cemented wood wool panels

“Cewood” cemented wood wool panels are made of locally available, high quality, 3 mm wood wool with standard Portland cement as a mineral binder. These panels can be used for their superb acoustic properties or as decorative panels in ceiling and wall systems.

Panels can also be used for construction application which is in scope of this project. They can be used together with timber frame to provide both insulation capabilities and structural integrity (Figure 1.35.). As this material has quite high density, it also has high thermal conductivity, which in case on nZEB requires it to be used together with other lower thermal conductivity materials.

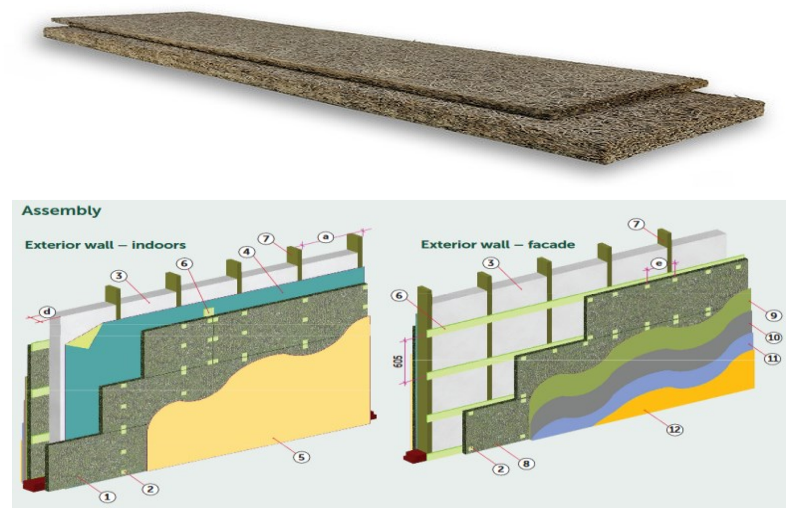

Figure 1.35. *“Cewood” cemented wood wool construction panels (upper)[20], possible applications of wood wool panel (lower)[21]*

“Akoterm” flax wool insulation mats

These flax thermal insulation plates are made of 85% flax fiber and 15% adhesives (Figure 1.36.). Material overall has similar properties of other wool insulation materials, its main advantage is its production from the bio-based raw materials and increased soundproofing capabilities[22] (Table 1.7.).

In scope of this project a flax insulation plates from Akoterm are reviewed, produced in Belorussia. Although not made completely locally, flax production in Latvia is sufficiently developed for such materials to also be produced more locally in coming years.

“Steico Zell” wood wool loose insulation

“Steico Zell” is wood wool loose thermal insulation material that is applied by air injection (Figure 1.36.). As in case of “Akoterm” flax insulation its properties are similar to those of

[20] http://www.cewood.com/products/construction-panels
[21] http://media.voog.com/0000/0039/1555/files/Timber-frame_house_Cewood.pdf
[22] http://akoterm.com/en_US/

other loose insulation materials, just with enhanced moisture regulation and environmentally responsible raw materials, as Steico is using wood that is only FSC certified[23].

Figure 1.36. *Akoterm flax insulation mats (left)[22], Steico Zell loos wood wool insulation[23]*

Table 1.7. Summary of Eco/local material properties

Properties and testing methods	Unit	Hempcrete panel	Ecoccocon straw 400 mm panel	Cewood construction boards	Akoterm Flax wool	Steico Zell
Type	-	Panel	Prefabricated panel	Board	Wool	Loose insulation
Bulk density	kg/m^3	400	100	400-500	30	32-40
Thermal conductivity (λ)	W/(mk)	0.070	0.043	0.066	0.038	0.038
Vapor diffusion resistance (µ)	(µ)	-	9.14 (clay plaster)	-	-	1-2
Sound insulation	dB	-	54	-	-	-
Compression strength	-	-	36.9 kN/m	-	-	-
Fire resistance	-	-	B-si,d0 (with clay plaster)	B-s1, d0	-	E

1.4.6. Standard insulation materials with lowered thermal conductivity

All materials in this group are of organic origin, they are known in construction industry to some extent, but their price or relatively recent introduction have led to limited usage. All these materials have poor reaction to fire because of their organic origin, but on the other hand can deliver significantly decreased thermal conductivity at only proportionally increased price, which makes all these materials interesting for possible use in nZEB.

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[23] http://www.steico.com/int/products/einblas-daemmung/steicozell/overview/

Polyurethane (PUR)

It is produced in an exothermic reaction between di- or polyisocyanate and polyether polyol. As all materials in this group it has high reaction to fire. Its thermal conductivity increases together with cell size (Schiavoni, D’Alessandro, Bianchi, & Asdrubali, 2016).

In scope of this work two products are reviewed – “Tenapors PUR DT” panels (Figure 1.36.) and BASF “Elastospray” sprayed insulation. Properties can be seen in Table 1.8.

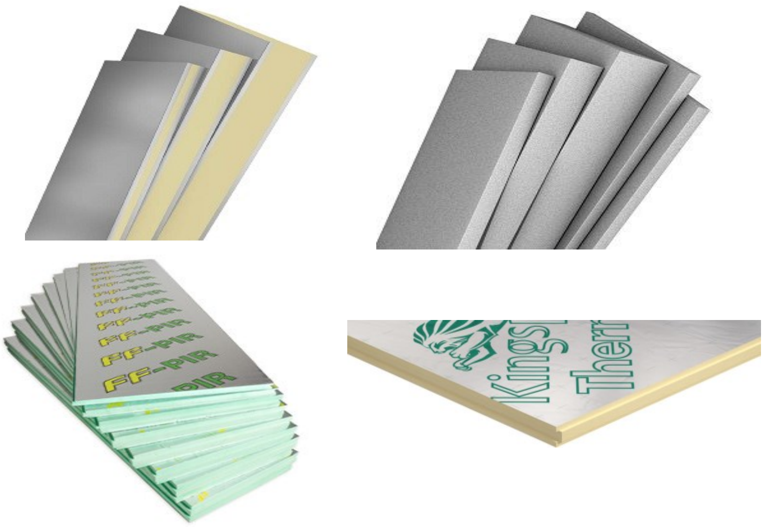

Figure 1.37. *“Tenapors PIR” (upper left), “Tenapors NEO EPS” (upper right), “Finfoam FF-PIR” (lower left), “Kingspan Therma” (lower right)*

Polyisocyanurate (PIR)

PIR materials are produced through similar reaction as PUR, only polyester-derived polyol and a higher proportion of methylene diphenyl diisocyanate is used. In general they have higher resistance to fire than PUR and also lower thermal conductivity (Schiavoni et al., 2016).

In scope of this work three products are reviewed – “Tenapors PIR DT” panels (Figure 1.37.) “Finfoam FF-PIR” (Figure 1.37.) and “Kingspan Therma TF70” (Figure 1.37.). Properties can be seen in Table 1.8.

Phenolic foam

Phenolic foam is also of organic origin, it differs from PUR and PIR with even lower thermal conductivity and higher density. Its thermal conductivity is more influenced by the water content (Schiavoni et al., 2016). In scope of this “Kingspan Kooltherm” is reviewed in Table 1.8.

Expanded polystyrene (EPS) with graphene additives

EPS is produced by evaporating that is added into polystyrene grains. EPS have high reaction to fire, so usually flame retardants are added in manufacturing process. Recently BASF have enhanced standard EPS properties by adding graphene nanoparticles that reflects heat, thus lowering thermal conductivity. In such way it is possible to achieve material with low thermal conductivity of around 0.03 W/m*K, but with only minimal increase in price, which also makes this material attractive for use in nZEB. "Tenapors NEO EPS 150" and is reviewed in Table 1.8.

Table 1.8. *PUR, PIR, Phenolic foam and EPS properties*

Properties and testing methods	**Unit**	**Tenopors PUR DT**[24]	**BASF Elastospr**[25]	**Finfoam FF-PIR**[26]	**Kingspan Therma TF70**[27]	**Tenapors PIR DT**[28]	**Kingspan Kooltherm**[29]	**Tenapors NEO EPS 150**[30]
Type	-	PUR	PUR (spray)	PIR	PIR	PIR	Phenolic foam	EPS
Bulk density	kg/m³	38	-	30	-	35	-	27
Thermal conductivity (λ)	W/(mk)	<0.024	0.028	0.022	0.022	<0.024	0.020	0.030
Compressive stress ar 10% deformation	kPa	120	200	100	100	>100	100	150
Reaction to fire	Class	F	E	E	E	F	C-s2,d0	E

1.4.7. Environmental impact of insulation materials

Research done by Tingley et al. (Tingley, Hathway, & Davison, 2015) quantifies and compares the environmental impact of three insulation materials: expanded polystyrene, phenolic foam and mineral wool insulation. It was found that expanded polystyrene had the lowest environmental impact in fourteen of the sixteen impact categories examined (Fig.1.38.). When applied to a typical dwelling, all three insulation materials demonstrated a net positive benefit over a thirtyyear life span due to the reduced heating requirements of the building. A study of embodied carbon also included PIR and woodfibre boards. This demonstrated that woodfibre board had the lowest embodied carbon, mainly due to carbon sequestration. Modest savings (e.g. 115 $kgCO_2eq$ if EPS is used instead of phenolic foam) can be made from insulation choice for a single house but these savings become much more significant if scaled across the large number of UK homes that would benefit from external wall insulation.

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[24] http://tenapors.lv/en/product-by-use-open/2/80
[25] http://www.polyurethanes.basf.com/pu/solutions/en/function/conversions:/publish/content/group/Arbeitsgebiete_und_Produkte/construction/spray_foam/Elastospray_DOP/NL17-0015-01-CPR-17_EN.pdf
[26] https://www.finnfoam.lv/files/dop/fi-1/FF-PIR/recent/Finnfoam_2017_en_FF-PIR%20ALI_141-FF-2017-06-06.pdf
[27] http://spu.studio.crasman.fi/file/dl/i/DiAxYA/uQpxTJjKjYOUTXkziMAqGg/CPR_2013_TF70_001_EN.pdf
[28] http://tenapors.lv/en/product-by-use-open/3/78
[29] https://www.kingspan.com/roe/el-gr/products/insulation/declaration-of-performance/kooltherm-k3-floorboard
[30] http://tenapors.lv/en/product-by-use-open/2/14

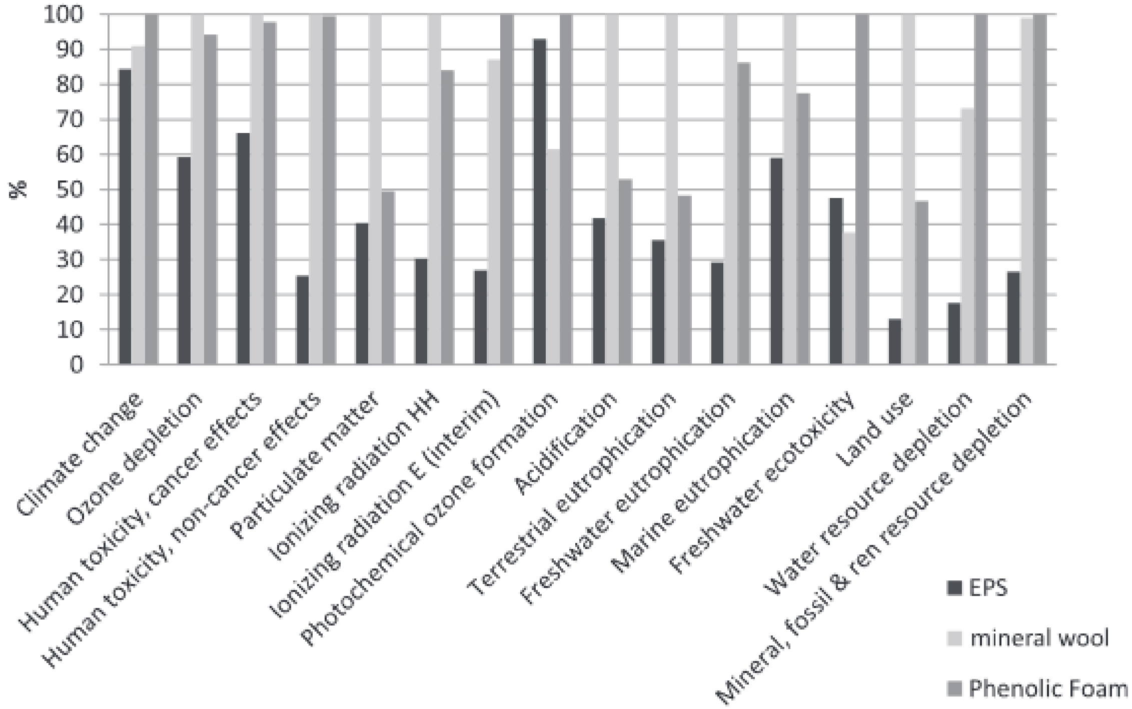

Figure 1.38. *Environmental impact category for the reviewed materials (Tingley et al., 2015)*

This study of Braulio-Gonzalo (Braulio-Gonzalo & Bovea, 2017) presents a methodology to analyze optimum insulation material for the building's envelope (roof, façade and floor) and its thickness to achieve energy demand reductions in the operation phase of the building, which is based on the Life Cycle Assessment and Life Cycle Costing methodologies to integrate both environmental and economic aspects, respectively. The system boundary includes the life cycle stages of product and use defined by recent European standards. A selection of eleven alternative insulation materials, both conventional and emerging ones based on natural products, were chosen to conduct the study. After applying the methodology to a single-family house in Spain and performing a sensitivity analysis, the results revealed that sheep wool and recycled cotton, jointly with traditionally used mineral and glass wool,

Table 1.9. *Materials used in the research of environmental impact of insulation*

Insulation material	Source	Density (kg/m^3)	λ (W/mK)	Specific heat (kJ/kgK)	Water vapour diffusion resistance factor (μ)	Commonest applications: Roof – Sloping	Roof – Flat	Façade – ETICS	Façade – Ventilated	Façade – Internal insulated	Floor
Conventional materials											
Glass wool (GW)	[22,19]	40	0.04	0.9–1.0	1–1.1	●	●		●	●	●
Mineral wool (MW)	[22,19]	45	0.035	0.8–1.0	1–1.3	●	●		●	●	●
Expanded Polystyrene (EPS)	[19]	25	0.034	1.25	20–70	●	●	●	●	●	●
Extruded Polystyrene (XPS)	[22,19]	30	0.035	1.45–1.7	80–150	●	●	●	●	●	●
Polyurethane (PUR)	[19]	45	0.032	1.3–1.45	30–170	●	●		●	●	●
Foam glass (FG)	[22,40]	110	0.04	1	$1 \cdot 10^{10}$		●			●	●
Cork (C)	[19]	170	0.04	1.5–1.7	5–30	●	●	●		●	●
Emerging materials (natural)											
Sheep wool (SW-blanket)	[42]	15	0.043	1.3–1.7	1.0–3.0	●	●		●	●	●
Sheep wool (SW-filling)	[42]	15	0.043	1.3–1.7	1.0–3.0	●	●			●	●
Recycled cotton (RC-blanket)	[42]	30	0.036	1.6	1–2	●	●		●	●	●
Recycled cotton (RC-filling)	[42]	15	0.044	1.6	1–2	●	●			●	●

should be promoted in the construction industry as they offer the highest eco-efficient performance among the analyzed insulation materials(Table 1.9., Fig. 1.39.). Reductions of up to 40% in energy demand compared to regulations standards can be achieved in the eco-efficiency context.

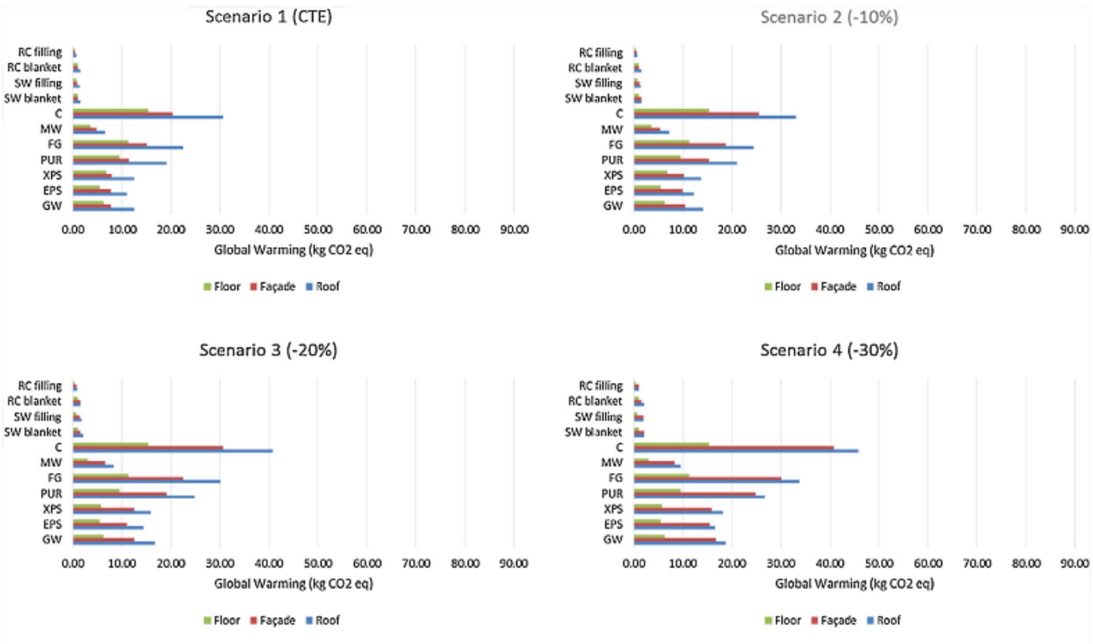

Figure 1.39. *Environmental impact (Global Warming, kg eq. CO_2) per 1 m^2 of each element of the building's envelope (roof, floor or façade), by type of insulation material and by scenario (Braulio-Gonzalo & Bovea, 2017)*

Conclusions

In the scope of this review, the aim is to develop know-how concerning an energy efficient and sustainable construction under the temperate climatic conditions and to find effective and functional thermal insulation materials and easy, convenient and quality assured mechanical integration technology, taking in account economic justification of such solutions.

It was proposed in this review to group all insulation materials in three major groups depending on their properties, manufacturing technology and raw materials used, and price. These groups were with the materials analysed:

- Advanced insulation materials
    - Aerogels
        - Cabot “Lumira” aerogel
        - Solera “Lumira” aerogel panels
        - Kalwall “Lumira” aerogel panels
        - Evonik Calostat
        - BASF Slentite
        - Proctor “Spaceboard”
    - Vacuum insulation panels (VIPs)
        - Promat SlimVac
        - Isover IsoVIP
        - va-Q-tec va-Q-vip
    - Gas filled panels (GFPs)
- Eco/local insulation materials
    - Hempcrete
    - Straw panels
    - Cemented wood wool panels
    - Flax wool insulation mats
    - Wood wool loose insulation
- Standard insulation materials with lowered thermal conductivity
    - Polyurethane (PUR)
    - Polyisocyanurate (PIR)
    - Phenolic foam
    - Expanded polystyrene (EPS) with graphene additives

General conclusions about the reviewed groups of materials:

- Transparent aerogel panels show great thermal insulation properties and could be used in construction of nZEB from technical side, but their main disadvantage is their price, which at this level of development allows it only to be used in pilot projects not in commercial scale projects.
- Non-transparent aerogels share similarly great thermal conductivity properties as transparent aerogels, but with reduced price. These materials could be used for nZEB applications where low thickness materials are necessary, such as renovations.
- VIP`s offer the lowest thermal conductivity, lower than 0.006 W/m*K, main drawback of these materials is the fragile nature, that requires extra care when installing and maintaining these materials, as well as lose of vacuum over time.
- Gas filed panels - advantage of these materials is their low thermal conductivity with low material usage, disadvantages are similar to VIPs – significantly difficult installation and use, as even little damage can destroy whole panel.

- Hempcrete is one of the materials that simultaneously provides a high-level energy efficiency as well as reduced impact on the environment. The CO_2 has been accumulated by the hemp shives through photosynthesis while growing and by the lime through carbonating in its hardening process, thus in total this material has ensured a negative CO_2 emission by locking more carbon dioxide in the material than unlocked during the production process, thus ensuring accumulation of the CO_2 at 6.67 to 136.65 kg CO2 eq./m^3 of material. Thermal conductivity of this material is 0.06 – 0.076 W/m*K. Overall these properties makes it very appropriate for nZEB construction
- Standard insulation materials with lowered thermal conductivity exhibit the best price/thermal conductivity ratio. This is countered by their low reaction to fire class and environmental impact.
- From their impact on environment only ecological and standard materials can be compared as there is insufficient research regarding environmental impact of most advanced building materials. The results from research show that overall the ecological material group show reduced impact on environment compared to standard insulation materials, regarding CO_2 emission and all other impact categories.

After conduction the review, following materials were chosen for the laboratory and in-situ tests: Evonik and Proctor aerogels, VIP`s, reflective insulation materials, hempcrete, straw panels, polyisocyanurate and phenolic foam insulation.

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