Greenhouse gas analysis of insulation options in residential energy retrofitting

Nicola Lolli The Research Centre on Zero Emission Buildings ZEB, Department of Architectural Design, History and Technology, NTNU, Alfred Getz vei 3, N-7491 Trondheim, nicola.lolli@ntnu.no

Anne Grete Hestnes The Research Centre on Zero Emission Buildings ZEB, Department of Architectural Design, History and Technology, NTNU, Alfred Getz vei 3, N-7491 Trondheim, annegrete.hestnes@ntnu.nu

Abstract

In the pursuit of stricter energy standards for buildings to reduce their share of energy use, the use of highly efficient insulation materials like aerogel and vacuum insulation has opened a path towards lighter construction in energy retrofitting, whereas commercially available materials, such as EPS and mineral wool, result in massive wall solutions. However, these new materials are notoriously energy intensive in production, resulting in high levels of embodied energy and emissions.

This work describes a comprehensive greenhouse gas analysis of the use of different insulation materials applied to residential building upgrades to passive house standard. It estimates the potential environmental disadvantages of using such materials in energy retrofitting.

A social housing complex from the late 1960s, located in Oslo, is used as test case. The building is upgraded to passive house standard. The facades are renovated by reducing the wall thermal conductivity to a U-value of 0.10 $Wm^{-2}K^{-1}$. This is achieved by applying correspondingly appropriate thicknesses of mineral wool, aerogel and vacuum insulation. A cradle-to-grave analysis is then performed on the facade components to determine the global warming potential of each proposed insulation option. Special attention is given to the share of the embodied emission over the building lifetime, by varying the electricity-CO_2 conversion factor as well as the lifetime of the renovated building. Comparisons between the resulting energy demand and embodied emissions are presented.

Results show that the shares of embodied emissions of the options with mineral wool, aerogel and vacuum insulation are 13%, 29% and 49% of the total building lifecycle emissions, respectively. Despite the fact that aerogel and vacuum insulation have a global warming potential which is between four and eight times higher than that of mineral wool, the resulting effect is a minimal difference between the retrofitting alternatives. This is due to the limited amount of mass of vacuum insulation and aerogel needed to obtain a U-value equivalent to that of the wall equipped with mineral wool.

Keywords: GHG emissions; VIP; Aerogel; Rockwool; Life cycle impact assessment; $CO_{2\text{-eq}}$ emissions

Introduction

Both the building industry and building stock are energy-intensive sectors and causes of significant GHG emissions. Production, installation, transportation and disposal of building materials, and the energy use for achieving indoor comfort, are the main forces driving the current energy consumption rate. According to many sources [WBCSD 2008, Uihlein and Eder 2010, Dodoo et al. 2011] the building sector in the EU area accounts for about 40% of the total primary energy consumption, which refers to the energy used during their operation phase, and shares 25% of CO_2 emissions [Fernandez and Wattersons 2011]. To follow the path of the Kyoto Protocol, several European countries have adopted various measures and regulations that address energy-saving strategies in the residential sector. However, the newest building standards do not suffice to reach the environmental targets if a consistent campaign of renovation of residential buildings is not set up. A study from Nemry et al. shows that the shares of energy use and CO_2 emissions of the newest residential constructions of the EU-25 countries score negligible values only [Nemry et al. 2010]. Clearly, the need for retrofitting of the existing stock is an urgent issue for European countries, particularly because the space heating is responsible for a high percentage of the total energy use in buildings.

According to the current trend, in the next 50 years the EU-27 residential stock will only increase its total living area by 1.46% annually. The dwelling size is estimated to grow by 0.9% per year, while the number of persons per household is projected to decrease by 0.5% [Uihlein and Eder 2010]. According to these projections, the future stock will therefore be characterized mostly by old buildings with very low thermal insulation performances, by an increasing living area per person and by a rising energy demand per unit. As a consequence, if radical measures are not used, the residential stock in need of renovation will grow.

The existing residential stock in the EU represents a high potential for energy retrofitting in terms of cost and efficacy of environmental load reduction. By applying currently-practiced measures of building insulation upgrade is possible to save up to 20% of the annual GHG emissions. This results in a reduction of 360 $CO_{2\text{-eq}}$ per year. Generally, roof insulation represents the highest potential for savings for single-family houses, while multi-family buildings benefit mostly from façade insulation and greater air-tightness [Nemry et al. 2010]. The energy saving measures aimed to increase the thermal resistance of the building envelope are generally cost-effective. Improving the insulation layer in external walls and roofs saves up to EUR 30 per ton of CO_2 while, in contrast, the application of photovoltaic panels costs between EUR 10 and EUR 20 per avoided ton of CO_2 [McKinsey&Company 2009].

It is clear that measures of energy conservation of the EU residential stock, through renovation activities, are critical in reducing the global energy use for space heating and, consequently, are effective in abating GHG emissions. In order to achieve effective reduction of total energy use in the EU area the residential stock should aim towards higher classes of energy efficiency, such A and A+. In this perspective, as the energy demand of the buildings is decreasing, the share of embodied GHG emissions gains more weight. So far, the appraisal of buildings based solely on the energy use does not provide a comprehensive picture of the performances of different retrofitting solutions. For this a life cycle assessment is necessary.

Objective

The objective of the work is to compare and assess the environmental impact of different insulation materials applied in the energy retrofitting of a housing complex, the Myhrerenga Borettslag, located in Oslo, Norway. A reference solution, which represents the actual accomplished renovation work of the Myhrerenga Borettslag [Klinski and Dokka 2010], is compared to three options with improved thermal resistance of the external walls using different insulation materials. The selected insulation materials are rock wool, vacuum insulation panels (VIP) and aerogel. To better evaluate the share of embodied emissions of the proposed insulation alternatives, the kWh-to-CO_2 conversion factor and the building lifetime are varied. The reference kWh-to-CO_2 conversion factor of the power grid is based on the model developed at the Research Centre on Zero Emission Buildings (ZEB), and this is compared to the EU average value and the Norwegian energy mix at inland production. The reference lifetime for the upgraded building is set to 50 years, and this is compared to a reduced lifetime of 25 years and an extended lifetime of 75 years.

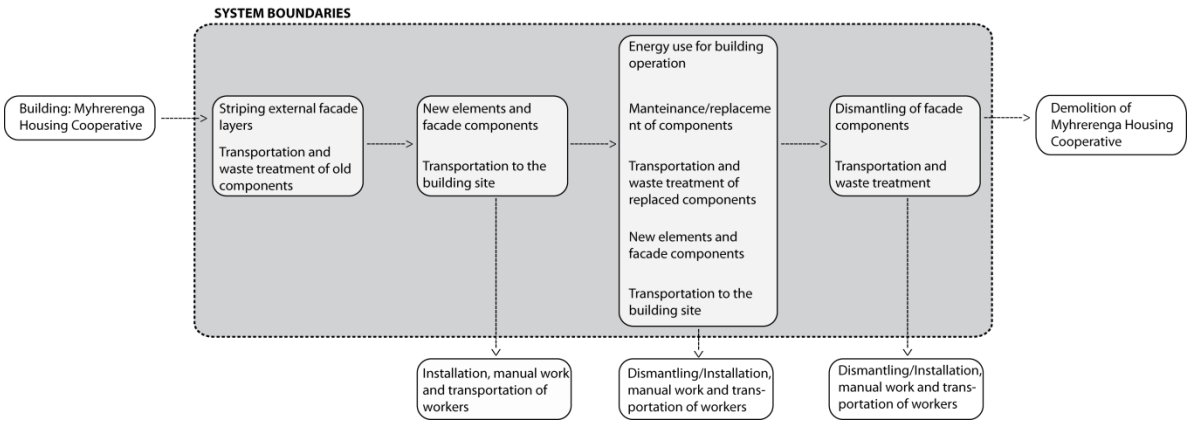

Figure 1 System boundaries of retrofitting scenarios.

Method

Global warming potential (GWP) is chosen as the common characterization method to quantify the contribution of GHG emissions (expressed as $kgCO_{2\text{-}eq}kg^{-1}$). Included are the processes of material resource use for building components, production of building components, transportation to the building site, maintenance cycle and substitution of damaged/old components, transportation to end-of-life (EOL) treatment plants, and waste treatment. The contributions are shown in Figure 1.

The reference building

The Myhrerenga Housing Cooperative represents one of several examples of residential blocks that have being shaping the urban landscape of most Norwegian towns and currently share approximately 23% of the entire Norwegian dwelling stock [Brattbakk and Thorbjørn 2004, Statistisk Sentralbyrå 2011]. The Cooperative is composed of seven identical buildings where each block has 24 apartments that are served by four stairwells positioned on the East side of the building. Partially enclosed balconies (loggias) lie on the West façade. The East and West facades of the reference building are shown in Figure 2.

The building structure is composed of an array of parallel reinforced concrete walls, which delimit each apartment and constitute the load bearing structure along with the concrete floors. The

external walls on the East and West sides mainly consist of a lightweight frame-and-cladding system, which has been commonly used in Norway. The wall construction is a wooden framework of 5x10 cm studs spaced every 60 cm. The cavity within the studs is filled with 10 cm thick Rockwool bats, and the internal and external finishing is made of gypsum plasterboards and wood sidings respectively [Norges byggforskinstitutt 1987]. The North and South walls are built with concrete sandwich panels with 8 cm of insulation. Windows, located on the East and West façades only, have been replaced in the 1980's and consist of wooden frames with double glass panes [Klinski and Dokka 2010] with a heat transfer coefficient of approximately 2.6 $Wm^{-2}K^{-1}$ [Byggforskserien 1981]. The roof construction is composed of an insulated wooden frame, with 10 cm of mineral wool, standing on the load-bearing concrete slab, while floors in the basement have a 5 cm Expanded Polystyrene layer only. Since the balcony slabs are fully exposed and abutting the concrete floors, problems of thermal bridging occur at all the structural connections. The existing energy supply system consists of a central electric-oil boiler and a hydronic system with radiators in each apartment. There is also a centralized fan system which removes exhaust air from apartments. Measured delivered energy demand reaches 300 $kWhm^{-2}y^{-1}$, something which is mainly the result of very poor thermal insulation of the external envelope, a consistent presence of thermal bridges along windows and balcony joints, and low air tightness of window frames and walls [Klinski and Dokka 2010].

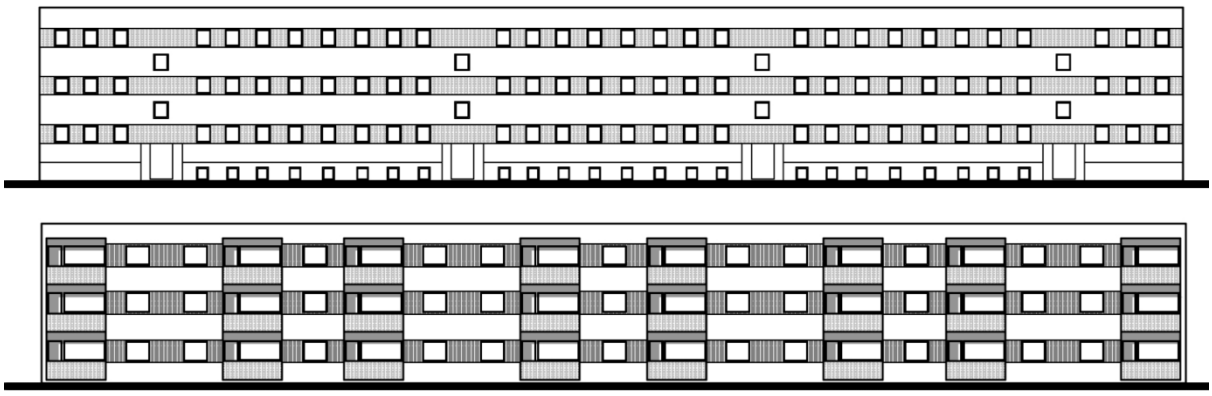

Figure 2 East and West facades of one residential block of the Myhrerenga Housing Cooperative.

Assumptions for the energy model

Only one of the 7 blocks of the Myhrerenga Borettslag is modelled. Of the 24 apartments of this block, only the most thermally significant apartments are fully described. These comprise six units of 54 m^2 each on the extremes of the building and six units of 64 m^2 each in the middle. The remaining 12 units are aggregated into 2 adiabatic zones. The indoor partitions of each residential unit are not geometrically described, but their approximate thermal mass is included in the energy calculation model. Three portions of the basement, two below the extreme apartments and one below the middle apartments, are included as unheated zones, as are the basement and the four stairwells. The remaining portion of the building is treated as an adiabatic zone.

Settings of indoor	Value	Schedule (hh/d/ww)
Occupancy	100%	16/7/52
Installed light power	1.95 Wm^{-2}	16/7/52
Installed appliance power	3.00 Wm^{-2}	16/7/52
DHW	5.1 Wm^{-2}	16/7/52
Infiltration rate	0.6 ach	24/7/52
Ventilation rate	0.023-0.026 $m^3s^{-1}m^{-2}$	24/7/52
Designed indoor temperature	21 C	16/7/52
Designed indoor temperature	19 C	8/7/52

Table 1 The variables used in the energy model.

Calculations are based on yearly energy use for heating, ventilation fans, water pumps, electric appliances, lighting appliances, heath pump use, and DHW use. The results are normalized to $1m^2$ of building conditioned area. The heating system is modelled as a single air-to-water heat pump that is linked to a single radiator in each apartment. Ventilation is provided by variable air volume units, which deliver fresh air at 0.023 $m^3s^{-1}m^{-2}$ in the 54-m^2 apartments and 0.026 $m^3s^{-1}m^{-2}$ in the 64-m^2 apartments. A heat-recovery system, consisting of a flat plate unit with 83% nominal efficiency, is linked to the ventilation system.

Assumptions for the life cycle model

According to many sources [Erlandsson and Borg 2003, Adalberth 1997a, Malmqvist et al. 2011, Kellemberg and Althaus 2009, Citherlet and Defaux 2007] the standard life cycle (LC) model for buildings is composed of seven stages (material production, transportation, construction, building use and maintenance, demolition, transportation and end-of-life) and is referred a “cradle to grave” LC. However, since this research is mainly focused on comparing GHG impact scenarios of different façade solutions through the life span of a block of the Myhrerenga Borettslag, the LC model has been simplified by excluding the demolition phase. The activities included in the LC model are presented in Figure 1. The calculation is based on [Adalberth 1997a], and the results are normalized to $1m^2$ of heated area.

Material	Waste treatment (%)			Factory gate-building site distance (km)	Means of conveyance	Waste at building site (%)	Notes
	Incineration	Landfilling	Recycling				
Argon[1]	-	-	-	25	Lorry 16-32t	0	[1] No end-of-life scenario for argon.
Paint[2]	100	-	-	175	Van < 3.5t	5	[2] End-of-life scenario not included in NHP2, sourced from [Blom et al. 2010].
Wood preservative[3]	100	-	-	50	Van < 3.5t	10	
Plaster[4]	-	100	-	150	Lorry 16-32t	5	
Concrete	-	-	100	150	Lorry 16-32t	5	[3] Impacts of end-of-life aggregated to wood products.
Gypsum	-	60	40	150	Lorry 16-32t	10	
Asphalt	100	-	-	150	Lorry 16-32t	10	[4] End-of-life scenario not included in NHP2, assumed as landfilled.
Plastic[5]	20	-	80	150	Van < 3.5t	7	
Sealants[5]	20	-	80	25	Lorry 16-32t	5	
Glass	-	20	80	25	Lorry 16-32t	0	[5] No specific fractions of the EOL scenario are defined in the NHP2 which are sourced from [Bohne et al. 2008].
Steel[6]	-	10	90	525	Lorry 16-32t	0	
VIP[7]	-	100	-	1525	Lorry 16-32t	3	
Aerogel[7]	-	100	-	1525	Lorry 16-32t	5	[6] End-of-life process not included in the NHP2, fractions sourced from [Bohne et al. 2008].
EPS	-	100	-	100	Lorry 16-32t	10	
Mineral wool	-	100	-	100	Lorry 16-32t	10	[7] End-of-life process not included in the NHP2, assumed as landfilling.
Wood	100	-	-	175	Lorry 16-32t	10	

Table 2 End-of-life scenarios, transportation distances, means of transportation and wastes at building site for the retrofitting scenarios.

Several authors [Adalberth 1997a, Blengini 2009, Gustavsson et al. 2010] report values of energy use for demolition and construction activities. According to [Adalberth 1997b] energy use for construction and demolition activities is 1% of the total energy use for a 50-year lifetime. Similar values are reported by [Blengini 2009, Gustavsson et al. 2010]. Since the contribution of these activities is small and since there is a lack of information regarding the installation and dismantling phases, the energy use from these stages has not been considered in the calculation.

The transportation distance from the building to the disposal site and end-of-life treatment plants is taken from [Adalberth 1997b] and assumed to be 20 km. Whenever possible, disposal scenarios of construction materials are obtained from the Nasjonal Handlingsplan for bygg-og anleggsavfall 2007-2012 [NHP2 2007], which was issued in 2007 and includes a proposal regarding the handling and disposal of building waste in Norway. Table 2 summarizes the disposal treatments for the materials of the reference building and the retrofitting scenarios. All materials are 100% sourced from primary materials with the exception of EPS, of which 45% is sourced from recycled material. There are no environmental credits for energy recovery associated with incineration. No system expansion or substitution is credited to the recycling processes.

Transportation of materials to disposal plants is done with 16-32 ton lorries. Transportation distances of materials from production sites to the Myhrerenga Borettslag are set according to the location of the closest production plants in Norway, and are itemized in Table 2, where the means of transportation, which refer to a study from [Blengini and Di Carlo 2010], are also reported. In the same table, information regarding the material waste due to cutting and rendering at the building site are taken from [Adalberth 1997a, Kellemberg and Althaus 2009, Gustavsson et al. 2010, Blengini and Di Carlo 2010]

In [Adalberth 1997a, Citherlet and Defaux 2007] the building lifetime is set to 50 years, while other sources uses lifetimes from 40 years [Chen et al. 2001], to 70 years [Blom et al. 2010, Blengini and Di Carlo 2010] and to 100 years [Gustavsson et al. 2010]. Regarding the case study of this research, the

building lifetime has been set using as reference the works of [Bergsdal et al. 2007, Sartori et al. 2008] where the building lifetime of Norwegian residential stock varies from 75 to 125 years. As a consequence, three different lifetimes after retrofitting were used for the 45-year old building: 25 years, 50 years and 75 years.

The operation phase also covers the maintenance of the façade components. Relevant data on maintenance cycles for Norwegian buildings are reported in [Byggforskserien 2010]. The length of time-intervals between each substitution/upgrading of building components depends on their technical quality and on the climatic and operational stress to which building parts are subjected. Since information on this is not available, it was decided to use average values, as reported in table 4 of [Byggforskserien 2010]. Energy use for transportation of workers from and to the building site during the renovation activities has not been included due to lack of data.

Emission impact data of materials production, transportation and waste treatment have been sourced from the Ecoinvent database [Ecoinvent 2010]. Impact data on aerogel is sourced from [Aspen Aerogel, Dowson et al. 2012], where a value of 4.2 $kgCO_{2\text{-}eq}kg^{-1}$ is reported. GWP value of VIP (8.06 $kgCO_{2\text{-}eq}kg^{-1}$) is extracted from a model developed by [Schonhardt et al. 2003]. No waste treatment scenario for aerogel and VIP is reported in current literature. They are here assumed to be landfilled as inert materials.

Conversion factors from electricity grid power (kWh) to $kgCO_{2\text{-}eq}$ are calculated for three different scenarios: European energy mix, Norwegian energy production only, and a projection of the future energy exchange within Europe developed by the Centre on Zero Emission Buildings (ZEB). The EU energy mix is calculated to be 0.361 $kgCO_{2\text{-}eq}kWh^{-1}$ [Graabak and Feilberg 2011] and the Norwegian inland production 0.019 $kgCO_{2\text{-}eq}kWh^{-1}$ [Entsoe, Eurostat]. The "ZEB energy mix" is derived by projecting the EU energy imports-exports scenario that optimizes the use of renewable sources to achieve a carbon-neutral electricity grid by 2054. Assuming a 60-years lifetime of a building erected in 2010, the average CO_2 conversion factor becomes 0.132 $kgCO_{2\text{-}eq}kWh^{-1}$ [Dokka 2011]. This method proposes a dynamic calculation that predicts the future $kgCO_{2\text{-}eq}$-to-kWh conversion factor according to:

$$R_{el} = \frac{361}{2} \cdot \frac{t_n - t_0}{lifetime}$$

where t_n is the time at which the CO_2 emissions from the EU electricity mix equals zero, which is assumed to be in 2054. t_0 is the time at which the calculation is started (e.g. the starting point of the building lifetime), and this is assumed to be 2012 in this case. *Lifetime* is the length of time the building is operated, here as 25, 50 and 75 years. Since the conversion factor is dependent on the building lifetime, three values derive from the life spans used in this work: 0.303 $kgCO_{2\text{-}eq}kWh^{-1}$ for 25 years, 0.152 $kgCO_{2\text{-}eq}kWh^{-1}$ for 50 years, and 0.101 $kgCO_{2\text{-}eq}kWh^{-1}$ for 75 years.

Retrofitting actions (scenarios)

In this work four different façade retrofitting solutions are compared. The option *reference building* consists of a package of thermal upgrades which have been effectively applied to the Myhrerenga Borettslag [Klinski and Dokka 2010]. Solutions named *Aerogel*, *Rockwool, VIP* represent a further upgrade of the reference building option. Details of external facades of retrofitting scenarios are presented in Table 3.

Details of external facades							
Reference building	0.12 $Wm^{-2}K^{-1}$	Aerogel	0.10 $Wm^{-2}K^{-1}$	Rockwool	0.10 $Wm^{-2}K^{-1}$	VIP	0.10 $Wm^{-2}K^{-1}$
Layers	Thickness	Layers	Thickness	Layers	Thickness	Layers	Thickness
Paint	0.1 mm	Paint	0.1 mm	Paint	0.1 mm	Paint	0.1 mm
Concrete tiling	8 mm	Concrete tiling	8 mm	Concrete tiling	8 mm	Concrete tiling	8 mm
Air gap	28 mm	Air gap	28 mm	Air gap	28 mm	Air gap	28 mm
Wind barrier	1 mm	Wind barrier	1 mm	Wind barrier	1 mm	Wind barrier	1 mm
Timber framework	200 mm	Timber framework	100 mm	Timber framework	250 mm	Timber framework	100 mm
Rockwool	200 mm	Aerogel	100 mm	Rockwool	250 mm	VIP	60 mm
OSB board	18 mm	OSB board	18 mm	OSB board	18 mm	OSB board	18 mm
Existing structure	100 mm	Existing structure	100 mm	Existing structure	100 mm	Existing structure	100 mm
Gypsum plasterboard	13 mm	Gypsum plasterboard	13 mm	Gypsum plasterboard	13 mm	Gypsum plasterboard	13 mm
Paint	0.1 mm	Paint	0.1 mm	Paint	0.1 mm	Paint	0.1 mm
Screws and connectors	-	Screws and connectors	-	Screws and connectors	-	Screws and connectors	-

Details of basement, roof, windows and balconies

Walls to non-conditioned areas are insulated with 140 mm of Rockwool slabs, or 40 mm VIP panels, or 100 mm Aerogel mats for each insulation alternative. The basement ceiling is insulated with 100 mm Rockwool slabs. Existing windows are substituted with triple glazing with Argon filling (0.79 $Wm^{-2}K^{-1}$). Existing prefabricated concrete balconies are substituted with new steel structures which are completely detached from the floor slabs. The original balustrades are substituted with glass panels. The roof is insulated with approximately 30 cm of blow-in polystyrene. The concrete walls delimiting the basement are insulated externally with 200-mm-thick expanded polystyrene slab (EPS), and the basement floor is equipped with 100 mm Rockwool slabs.

Table 3 Technical characteristics of the retrofitting alternatives.

Results

The results from the analysis of the different retrofitting scenarios are presented as normalized to 1 m^2 of heated building area per year. The first set of data shows the energy demand of the proposed retrofitting options and the share for different end-uses. The results for the retrofitting options using a 50-year lifetime are then presented. Lastly, the results from the extended and reduced building lifetime scenarios are shown. Within each lifetime-scenario, the contributions to the environmental impact from the three proposed energy mixes are compared.

Lifetime scenarios

The first aim of this work is to evaluate the environmental impact of different energy retrofitting packages applied to the facades of a residential block. Figure 3 shows the energy demand of the proposed upgrading options, in which the shares of single end-uses are presented. The heating and the DHW system are aggregated as they are served by the same air-to-water heat pump. The heating energy demand is 2 $kWhm^{-2}y^{-1}$ higher in the reference building than in the other options, due to its slightly lower insulation value, as presented in Table 3.

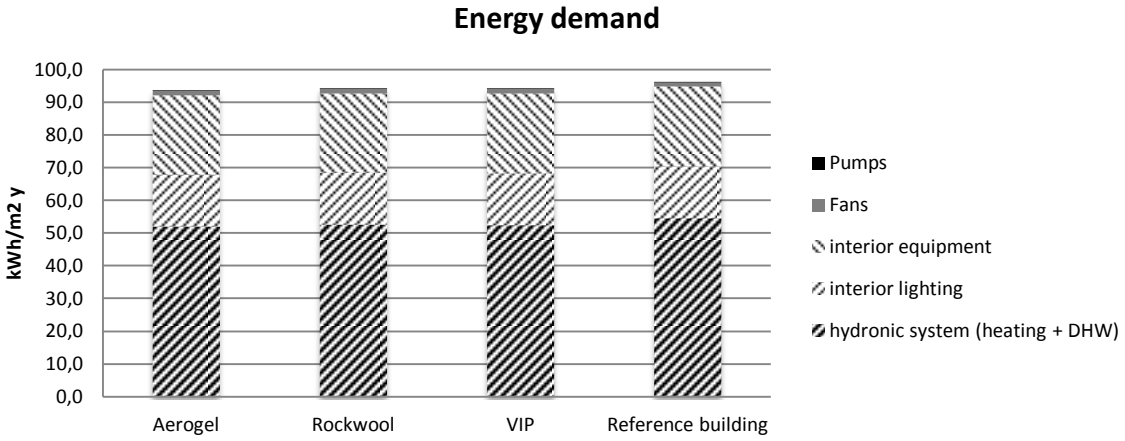

Figure 3 Composition of the yearly energy demand of the four retrofitting alternatives. Values are normalized to 1 m^2 of building heated area.

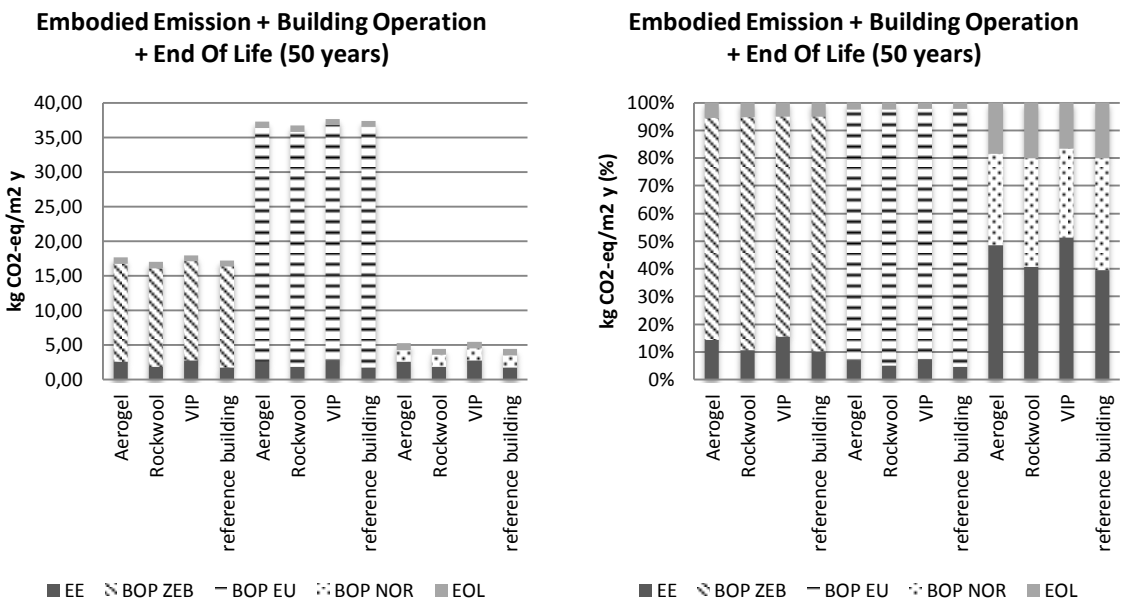

Figure 4 GHG emissions for retrofitting alternatives for the 50-year lifetime scenario. The bars show the Embodied Emissions (EE), the emissions from energy use for operation using the "ZEB energy mix" (BOP ZEB), the European energy mix (BOP EU), and the Norwegian energy mix (BOP NOR), and the emissions from the end-of-life treatment (EOL). All values are normalized to 1 m^2 of heated building area for 1 year.

The $CO_{2\text{-eq}}$ emissions of the same four retrofitting scenarios using the ZEB, the EU and the NOR energy mixes are presented in Figure 4. Differently from Figure 3, including the embodied emissions of the façade components throughout their life span changes the even distribution of energy uses. By adding the contribution of the $CO_{2\text{-eq}}$ emissions from material production and waste treatment, the option *Rockwool* and the reference building present the two lowest values (16.97 and 17.20 $kgCO_{2\text{-eq}}m^{-2}y^{-1}$ respectively). This is mainly due to the minor emission impact of mineral wool. However, the upgrades with aerogel and VIP are eventually 1 $kgCO_{2\text{-eq}}m^{-2}y^{-1}$ higher because of the use of more energy-intensive insulation materials. The environmental impact of the production and the end-of-life phases of the aerogel and VIP options represents approximately 20% of the total life cycle emissions. By introducing a lower carbon intensive energy mix, the share of embodied emissions of

the different retrofitting scenarios rises from 60% in the reference building to 68% in the VIP design, as presented in Figure 4. Clearly, a more carbon-intensive energy mix reduces the share of emissions from production and the end-of-life treatment to the smallest number. This is, for the EU mix, not higher than 10%.

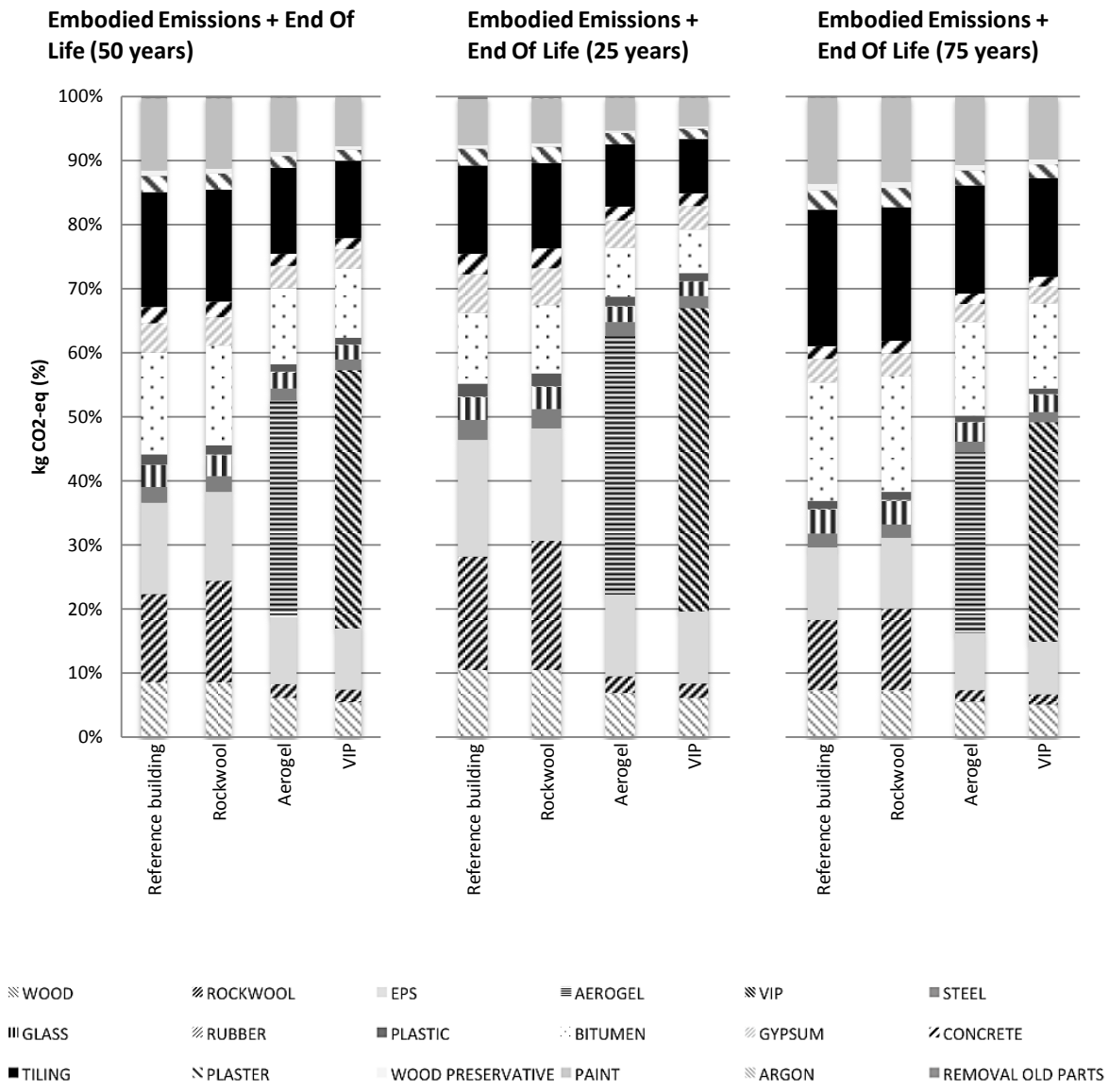

Figure 5 Composition of GHG emissions for the retrofitting alternatives for the 50-year, 25-year, and 75-year lifetime scenarios.

As presented in Figure 5, the main contributors to the environmental impact in all retrofitting scenarios consist of paint and finishes, concrete tiling, asphalt shingles, and insulation materials (EPS, Rockwool, VIP and aerogel). The paint, which is applied to both indoor and outdoor surfaces, including windows frames, is alkyd paint diluted with 60% water and has a GPW of 2.74 kgCO2-eqkg-1. Despite its initial small quantity, its frequent maintenance cycle (a new coating every 10 years) and its high-GWP due to waste-treatment (2.38 kgCO2-eqkg-1) makes it an important contributor to the total environmental impact in the 50-year and 75-year lifetime scenarios. The main reason for the high contribution of concrete cladding is due to its high mass, which alone is approximately 14% of the total mass composition for each of the renovation designs. Bitumen is mainly used as asphalt

shingles, laid to provide a waterproof layer to the flat rooftop and its substantial contribution to the overall $CO_{2\text{-eq}}$ emissions is due to the waste treatment process, which has a 4-times higher GWP than the production process of the material itself. With a complete substitution of the asphalt layer every 25 years, bitumen represents the 2nd ranked impact contributor for the reference building in the 50-year and 75-year lifetime scenarios. Insulation materials represent the other large family of contributors, with a share between 30% and 53% of the total GHG emissions, for the reference building and the VIP option for the 50-year lifetime scenario, respectively. Comparing the reference building and the *Rockwool* option, the 2%-reduction in the emissions burden due to the lower energy demand for building operation is counterbalanced by an overall 2% increase in the $CO_{2\text{-eq}}$ emissions due to the thicker insulation layer. The 50-mm thicker mineral wool layer used in the *Rockwool* option causes a 15% higher impact of the Rockwool alone. Mainly because of its high mass (4th ranked in both *Rockwool* and *reference building* scenarios), Rockwool contributes alone between 15% and 18% of the total GHG emissions in the 50-year lifetime scenario.

The $CO_{2\text{-eq}}$ emissions of EPS, which is mainly used as roof and basement wall insulation share between 9% and 18% of the total burden in all alternatives. It differs from mineral wool in that the contribution of EPS is mainly due to a higher GWP from production (2.59 $kgCO_{2\text{-eq}}kg^{-1}$) and from the end-of-life treatment. In the retrofitting alternatives with aerogel and VIP for the 50-year lifetime scenario, the insulation materials clearly are credited with the highest contribution to the total environmental impact. Aerogel and VIP share between 35% and 40% of the total GHG emissions, respectively. Despite the fact that aerogel and VIP have between 29% and 49% less mass than the mineral wool in the *Rockwool* option, their much higher GWP from production increases the overall $CO_{2\text{-eq}}$ emissions by 20% and 24%, respectively. It is important to notice that for both aerogel and VIP no information is available regarding the environmental impact of the waste treatment process, which has therefore been assumed to be the same as landfilling of inert construction materials. It can be assumed that other end-of-life scenarios are likely to vary the final GWP of the above insulation materials. The emission impact figures from transportation of materials from the production plant to the building site and to the waste treatment plant are aggregated in Figure 5. Shares of impact due to transportation vary from 2% for the concrete cladding to 22% for the Scandinavian softwood in the 50-year lifetime scenario. The greater distance from which aerogel and VIP are delivered significantly increases the impact of transportation, and ranges from 2.3% of the total for Rockwool to 7.6% for aerogel. It is important to remember that these figures relate to the share of the lifecycle environmental impact of the single component, and not to the entire renovation option. The impact of transportation of components accounts for 5% of the total GHG emissions of the *Rockwool* solution and does not vary significantly for the other scenarios.

Since the “ZEB energy mix” is based on future projections of EU energy exchanges, halving and extending the building lifetime greatly affects the environmental impact due to building operation. For the 25-year scenario there is not a large difference between using the ZEB energy mix and the EU energy mix (Figure 6). On the other hand, extending the lifetime to 75 years makes the building benefit from the close-to-zero conversion factor. It is worth noticing that in the “ZEB mix” the share of emissions of the production and end-of-life phases of the *reference building* is constant for the three lifetime scenarios. It is approximately 20%. On the other hand, in the EU and the NOR mixes it varies between 6-16% and 55-79% for the 75 and the 25-year scenarios, respectively. The end-of-life phase gains more weight the more the building lifetime is extended, especially in the NOR energy mix. In the *reference building*, it goes up from a 15% share to 26%, for the 25 and 75-year lifetimes,

respectively. Clearly, the materials for which the final emission impact is mostly affected by the maintenance cycle have higher fluctuations when varying the lifetime, as in the case for paint. For the 25-year scenario, insulation materials dominate the composition of retrofitting packages. In these, single VIP and aerogel components shares 47% and 40% of the total $CO_{2\text{-eq}}$ emissions, respectively (Figure 5). The share of the environmental burden of mineral wool for the retrofitting option *Rockwool* is four times higher than that of the *reference building*. On the other hand, in the 75-year scenario, the differences between different insulation alternatives are very small, and the share of the total emissions due to insulation materials, including EPS, is between 23% and 45%, as shown in Figure 5.

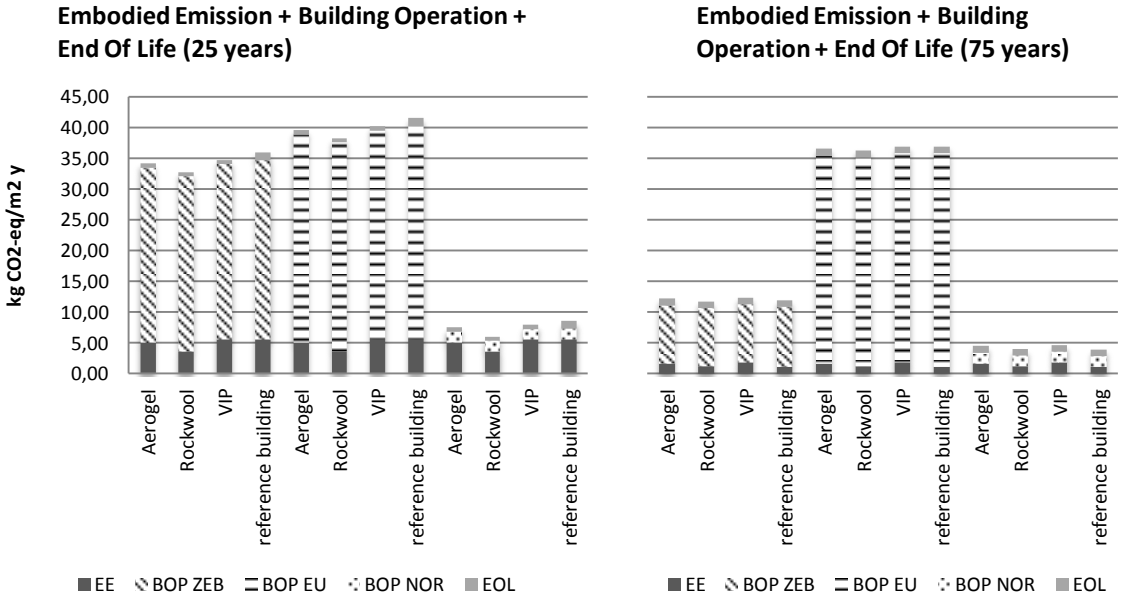

Figure 6 GHG emissions for retrofitting alternatives for the 25-year and the 75-year lifetime scenarios. The bars show the Embodied Emissions (EE), the emissions from energy use for operation using the "ZEB energy mix" (BOP ZEB), the European energy mix (BOP EU), and the Norwegian energy mix (BOP NOR), and the emissions from the end-of-life treatment (EOL). All values are normalized to 1 m^2 of heated building area for 1 year.

Discussion

The uncertainty and the choice of data used in this work might influence the results presented. Specifically, the information regarding the maintenance cycle, and the GWP of aerogel and VIP, might be critical to the results.

Maintenance cycles of building components and materials have been chosen according to the report *Intervaller for vedlikehold og utskifting av bygningsdeler*, where the medium rate of substitution of components has been chosen. It must be noted that according to [Byggforskserien 2010] the substitution rate derives from the technical quality of the component and the climatic stress to which the same element is subjected. Since this information is not available, the authors decided to choose a medium substitution rate, which is equivalent to assigning a low climatic stress to low-quality components or a high stress to good and very good components. However, since some materials, such as paints, have very short lifetimes, the difference between medium and high subtitution rates is 100%, while between medium and low is 50%. Clearly, choosing a shorter lifetime for such

materials definitely affects both the total emission impact and the share they have in the building composition, especially for the extended lifetime scenario.

The environmental impact due to transporting workers to the building site during the installation/dismantling phases of components has not been included in the calculation due to lack of data. This aspect has been studied by [Blom et al. 2010], who report that the impact of the transportation of workers can be up to 22% of the total emissions. Clearly, in addition to a higher substitution rate, this factor can be critical for determining the final environmental impact. However, since this work is mostly focused on comparing different insulation materials, for which the service life is equal to the building lifetime, this aspect is not very relevant.

Information regarding GWP values of aerogel and VIP are very scarce in literature. So far, the sources that were found and investigated are for aerogel from [Aspen Aerogel, Dowson et al. 2012]. Regarding the impact assessment of VIPs the report by [Schonhardt et al. 2003] was used. The very recent study by Dowson et al. compared the GWP of Spaceloft aerogel, as claimed by Aspen Aerogel, with the production of a lab sample at the University of Bath facilities. According to Dowson et al. the $CO_{2\text{-eq}}$ emissions associated with the sample produced in the University of Bath laboratories are between 4.4 and 23 times higher than the Aspen Aerogel claim. However, as stated by Dawson et al., by increasing the production to an industrial scale, using more energy efficient equipment and recycling some of the chain sub-products, it is possible to reduce the $CO_{2\text{-eq}}$ burden down to 1-3.4 times higher than the Spaceloft production.

Conclusions

The GHG emissions of three building renovation packages equipped with Rockwool, VIP and aerogel has been compared with a reference retrofitting solution of a residential block in Oslo. Results for the energy demand of the building show that the improved insulation layer saves up to 2% of the yearly energy demand for all the proposed insulation alternatives. The results of the LCA analysis show that the alternatives with aerogel and VIP result in an approximately 3% higher impact than the Rockwool solution, which is, on the other hand, equivalent to the reference building. Calculation has been performed for three different building lifetime scenarios and kWh-to-kg$CO_{2\text{-eq}}$ conversion factors, which are respectively: 50, 25 and 75 years, 50-years future projection of EU energy exchange ("ZEB energy mix"), EU energy mix at present, and Norwegian-export only. By extending the lifetime from 50 to 75 years the total $CO_{2\text{-eq}}$ burden is on average reduced by 25%, while for a 25-year lifetime it doubles when using the "ZEB energy mix". By introducing the EU and the Norwegian-export mixes, the total GHG emissions of each retrofitting alternative varies by up to 20%. Results from the analysis of the contribution of each component show that by increasing the building lifetime, materials which undergo higher substitution rates, such as paints and roof waterproofing layers, can contribute up to 25% of the building emission burden. In conclusion, results presented in this work show that the choice of any of the proposed insulation materials for a retrofitting package has a very low relevance (on average 2-3% difference) in regard to the final $CO_{2\text{-eq}}$ emissions for the retrofitted building. However, limitations to the GWP source data for VIP and aerogel require further investigation to better understand if the presented values are subject to wider variations, as may be expected.

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