Environmental perspective on two glazing typologies

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Abstract

Stricter energy regulations for energy use in buildings require new construction to be equipped with increasingly thicker insulation layers and minimal surfaces for glazing in cold climates. In recent years a new type of window has been proposed as a way to overcome the notoriously low thermal performance of transparent surfaces. In order to reach such performances, this glazing type has been equipped with monolithic aerogel as the glass-pane filling.

The scope of this study is a comprehensive analysis of greenhouse gas emissions from the partial substitution of typical triple-glazing-with-argon units with double-glazing-with-monolithic-aerogel units in residential building upgrades.

A social housing complex from the late 1960s, located in Oslo, is used as a test case. The building is fully upgraded using passive house solutions. The new facades have walls with a U-value of 0.10 $Wm^{-2}K^{-1}$ and triple-glazing-with-argon units with a U-value of 0.79 $Wm^{-2}K^{-1}$. In this study approximately 30% of the glazing area is substituted with double-glazing-with-aerogel units with a U-value of 0.50 $Wm^{-2}K^{-1}$. A cradle-to-grave analysis is performed on the facade components to determine the global warming potential of the two proposed glazing options. Differences in the share of the embodied emission over the building lifetime when increasing the total window-to-wall ratio from 24% to 33% and to 50% are also investigated. In addition, various maintenance schedules are used to evaluate the differences in emissions embedded in the façade components. Comparisons between the resulting energy demands and embodied emissions are presented.

Preliminary results show how the option with aerogel glazing is effective in reducing the annual heating demand by 7%. This increases to 18% for the façade design with a 50% window-to-wall ratio. The better insulation value of aerogel glazing effectively reduces the thermal losses while at the same time allowing passive solar gains. In addition, the mass of aerogel employed for glazing insulation does not significantly change the total embodied emissions of the façade. This suggests that the use of this window type is environmentally positive.

Keywords: $CO_{2\text{-eq}}$ emissions; Aerogel glazing; Triple glazing with argon; Life cycle impact assessment; Environmental impact;

Introduction

Both the building industry and building stock are energy-intensive sectors and causes of substantial GHG emissions. Production, installation, transportation and disposal of building materials, and the

energy use for achieving indoor comfort demand 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 employed during the operation phase of buildings, 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.

The stricter energy codes have resulted in use of massive insulation layers and small glazing areas to reduce the energy demand in both new and renovated buildings. To overcome the low thermal resistance of the transparent surfaces, multi-glazing types of windows have been developed of which a wide variety is available on the market today. Triple-low-energy-glass windows with argon filling, for instance, represent an effective energy-saving solution. However, these technologies have the drawback that they drastically reduce the amount of natural light that passes through the glass due to use of many coated layers. This condition can be favorable at medium latitudes (such as in central Europe) where there is a good solar radiation and cold winters. However, it can be disadvantageous at high latitudes (such as in Scandinavian countries) where the solar radiation in winter is low in terms of both hourly availability and quantity.

Glazing with aerogel filling has been proposed as a technology capable of providing natural light with the benefit of higher insulation values than classic triple and quadruple glazing solutions. Products from Okalux and Kalwall, for instance, provide a stunning 0.3 $Wm^{-2}K^{-1}$ but at the sacrifice of losing visible transmittance. On the other hand, recent studies have demonstrated that, by taking advantage of the optical properties of aerogel, it is possible to produce double-glazing windows that not only have a very low U-value (0.5 $Wm^{-2}K^{-1}$) but also have a higher visible transmittance than the correspondingly insulated standard alternative [Schultz and Jensen 2008, Schultz et al. 2005]. Simulations of the energy consumption of a single house insulated according to the passive house standard, located in Denmark, show that the option with aerogel glazing represents a 19% energy savings [Schultz and Jensen 2008]. In this perspective, windows insulated with aerogel, even if still at the prototyping stage, represent a promising solution to achieve high insulation levels without scarifying the access to natural light. However, aerogel, due to its production process, is an energy intensive material. Existing data for the global warming potential (GWP) of aerogel varies depending on the drying procedure and lies between 4.2 $kgCO_{2\text{-}eq}kg^{-1}$ and 14.3 $kgCO_{2\text{-}eq}kg^{-1}$ [Dowson et al. 2012]. It is interesting, then, to investigate to which extent the environmental disadvantages of using aerogel as an insulating material for windows balance the energy savings derived from the use of such glazing solutions.

Objective

The objective of the work is to compare and assess the environmental impact of two different glazing technologies applied in the energy retrofitting of a housing complex, the Myhrerenga Borettslag, located in Oslo, Norway. The proposed window technologies are a window with triple-low-energy-glazing and argon filling, and a window with double-glazing with aerogel filling. A reference solution, which represents the actual completed renovation of the Myhrerenga Borettslag [Klinski and Dokka 2010], is compared to two options with larger glazing areas and thicker insulation layer in the facades. The reference building has a total glazing area of approximately 24% and the improved designs have 24%, 33% and 50% windows-to-wall-ratios, respectively. The share of aerogel windows is approximately 28% in the facades with 24% and 33% window-to-wall-ratios, and it is approximately

39% in the façade with 50% window-to-wall-ratio. Since the glazed part of a façade is the one which is subject to higher substitution rates, different maintenance schedules are proposed to better evaluate the share of embodied emissions of the proposed glazing alternatives.

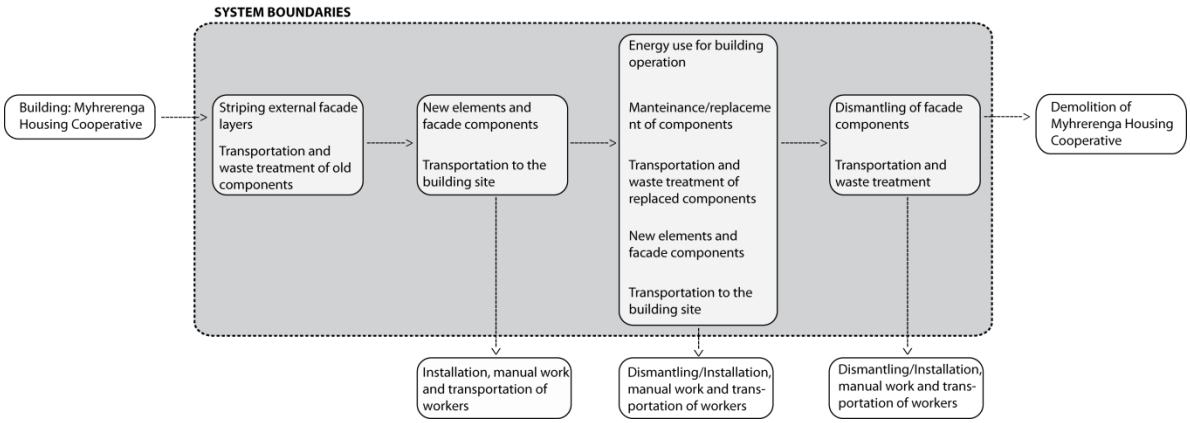

Figure 1 System boundaries of the retrofitting scenarios.

Method

The global warming potential (GWP) is chosen as the common characterization method to quantify the contribution of $CO_{2\text{-eq}}$ emissions. Included are the processes of material resource use for building components, production of building components, transportation to the building site, maintenance 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 divided in eight units per floor plus a basement, for a total of 168 apartments. The apartments, which face both East and West, vary from 54 m^2 (six units per block) to 68 m^2 (18 units per block) and are served by four stairwells positioned on the East side of the building. Partially enclosed balconies (loggias) lie on the West façade. Details of the building construction, the heating system, and the thermal properties of the transparent and opaque surfaces before and after renovation are available from [Klinski and Dokka 2010].

Assumptions for the energy model

Only one of the seven 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 environmental controls and variables are tuned according to [NS 3700:2010, NS 3031:2007] and are summarized in Table 1.

Class	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.

The calculations are based on yearly energy use for space heating, DHW and appliances. 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.

According to [Schultz and Jensen 2008, Schultz et al. 2005] a double-glazing unit with 20-mm-thick silica aerogel insulation evacuated at 10 hPa and equipped with a butyl sealant and polystyrene spacer would have a 0.50 $Wm^{-2}K^{-1}$ centre U-value and a 0.75 g-value. Similar values for double-glazing aerogel units are presented by [Duer and Svendsen 1998, Rubin and Lampert 1983]. Since aerogel-vacuum-insulated windows do not exist as a commercial product at present, data used in this research are extracted from experimental analysis by other groups. Specifically, light transmission properties and thermal properties of monolithic aerogel are sourced from [Duer and Svendsen 1998, Hutchins and Platzer 1996]. In the retrofitting packages proposed here, the aerogel glazing is composed of two 3-mm-thick clear glass panes and one 20-mm-thick layer of monolithic aerogel. The triple glazing is composed of three 3-mm-thick low-energy glass panes and two 10-mm-thick argon layers (Table 3). The U-values of the two window alternatives are 0.50 $Wm^{-2}K^{-1}$ and 0.79 $Wm^{-2}K^{-1}$, for the aerogel and the argon respectively. The solar heat gain coefficients are 0.73 and 0.40, for the aerogel and the argon respectively. The visible transmittances are 0.71 and 0.62, for the aerogel and the argon respectively.

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] a 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 it is referred to as a “cradle to grave” LC. However, since this research is mainly focused on comparing $CO_{2\text{-eq}}$ 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].

Several authors [Adalberth 1997a, Blengini 2009, Gustavsson et al. 2010] report values of energy use for construction and demolition activities. According to [Adalberth 1997b] energy use for construction and demolition activities is only 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 included in the calculation.

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	
Aerogel[7]	-	100	-	1525	Lorry 16-32t	5	
EPS	-	100	-	100	Lorry 16-32t	10	[6] End-of-life process not included in the NHP2, fractions sourced from [Bohne et al. 2008].
Mineral wool	-	100	-	100	Lorry 16-32t	10	
Wood	100	-	-	175	Lorry 16-32t	10	[7] End-of-life process not included in the NHP2, assumed as landfilling.

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

Glazing option	Substitution rate (years)			
	Long	Medium	Short	Super-short
Triple glazing with argon	50	40	20	20
Double glazing with aerogel	50	40	20	10

Table 3 The maintenance scenarios for the two glazing types. Substituion rates of other materials are sourced from [NHP2 2007].

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 for construction materials are obtained from the Nasjonal Handlingsplan for bygg-og anleggsavfall 2007-2012 [NHP2 2007], which was issued in 2007 and which includes a proposal regarding the handling and disposal of building waste in Norway. Table 2 summarizes the disposal scenario for the materials studied in this work. 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 material 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 trasnportation, 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 use lifetimes spanning 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]. In our case study, the building lifetime has been set taking as reference the works of [Bergsdal et al. 2007, Sartori et al. 2008] where the building lifetime of the Norwegian residential stock varies from 75 to 125 years. As a

consequence, the lifetime after retrofitting is set to 50 years. Considering that the building was built 45 years ago, the proposed time represents the medium value of the findings of Bergsdal et al. and Sartori et al.

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 windows are a critical building component, it was decided to use short, medium and long substitution rates, as reported in table 4 of [Byggforskserien 2010]. Since aerogel glazing is supposed to be more fragile than the triple glazing due to the vacuum within the two glass panes, a super-short substitution rate is proposed only for this window technology. The maintenance scenarios for the windows are shown in Table 3. Energy use for transportation of workers to and from the building site during the renovation activities has not been included due to lack of data.

Emission impact data for material production, transportation and waste scenarios have been sourced from the Ecoinvent database [Ecoinvent 2010]. Impact data for aerogel is sourced from [Aspen Aerogel, Dowson et al. 2012], where a value of 4.2 $kgCO_{2\text{-}eq}kg^{-1}$ is reported. In current literature there is no waste treatment scenario for aerogel. It is here assumed to be landfilled as inert materials.

The conversion factor from electricity grid power (kWh) to $kgCO_{2\text{-}eq}$ is calculated according to a projection of the future energy exchange within Europe developed by the Centre on Zero Emission Buildings (ZEB). This "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 50 years. From the above, the conversion factor is calculated to be 0.152 $kgCO_{2\text{-}eq}kWh^{-1}$.

Glazing alternatives

In this work three façade solutions with different windows-to-wall-ratios and different window technologies 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]. In the solution named *24% argon* the opaque insulation layer of external facades is improved. In the options *33% argon* and *50% argon*, the windows-to-wall ratio is increased to 33% and 50%, respectively, in addition to an improvement of the insulation layer of external facades. The alternatives named *24% aerogel*, *33% aerogel* and *50% aerogel* represent the different solutions with the aerogel windows and with the same insulation package for the opaque walls proposed as in the options with argon windows. Details of external facades and glazing alternatives are presented in Table 4, and illustrations of the different façade designs are shown in Figure 2.

Details of external facades							
	Reference building	24% argon	33% argon	50% argon	24% aerogel	33% aerogel	50% aerogel
Opaque walls	Thickness	Thickness	Thickness	Thickness	Thickness	Thickness	Thickness
Ceramic tiling	8 mm	8 mm	8 mm	8 mm	8 mm	8 mm	8 mm
Air gap	28 mm	28 mm	28 mm	28 mm	28 mm	28 mm	28 mm
Wind barrier	1 mm	1 mm	1 mm	1 mm	1 mm	1 mm	1 mm
Timber framework	200 mm	250 mm	250 mm	250 mm	250 mm	250 mm	250 mm
Rockwool	200 mm	250 mm	250 mm	250 mm	250 mm	250 mm	250 mm
OSB board	18 mm	18 mm	18 mm	18 mm	18 mm	18 mm	18 mm
Existing structure	100 mm	100 mm	100 mm	100 mm	100 mm	100 mm	100 mm
Gypsum plasterboard	13 mm	13 mm	13 mm	13 mm	13 mm	13 mm	13 mm
Paint	0.1 mm	0.1 mm	0.1 mm	0.1 mm	0.1 mm	0.1 mm	0.1 mm
Screws and connectors	-	-	-	-	-	-	-
Windows	3-10-3-10-3 argon	3-10-3-10-3 argon	3-10-3-10-3 argon	3-10-3-10-3 argon	3-10-3-10-3 argon	3-10-3-10-3 argon	3-10-3-10-3 argon
					3-20-3 aerogel	3-20-3 aerogel	3-20-3 aerogel
Total share	24%	24%	33%	50%	24%	33%	50%
Share of aerogel	-	-	-	-	28%	28%	39%

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 and self-supported by columns. The original balustrades are substituted with glass panels. The roof construction consists of a timber frame lying on a concrete slab creating an air gap between the lower slab and the above covering of approximately 30 cm, which is filled with 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 4 The technical characteristics of the glazing alternatives.

Results

The first set of data shows the energy demand of the proposed glazing 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 variation of the maintenance scenarios are shown.

Glazing alternatives

The energy use for the building operation for the different glazing alternatives is presented in Figure 3. The difference between the solutions with increased areas of triple-glazing with argon is no more than 7%. The solution *50% argon* uses 7.1 $kWhm^{-2}y^{-1}$ more than the solution *24% argon*, while the solution *33% argon* has a similar energy demand to the reference building (97.1 $kWhm^{-2}y^{-1}$ and 96.2 $kWhm^{-2}y^{-1}$, respectively). This is because the lower thickness of the mineral wool insulation of the reference building is balanced by the increased glazed surface. The solutions with aerogel glazing also show very small differences in energy use. It is limited to a 2 $kWhm^{-2}y^{-1}$ difference between the *24% aerogel* and the *50% aerogel* alternative. However, the solutions with aerogel glazing save up to 10% in yearly building energy use when compared to the windows with argon. This is because of the lower thermal transmittance of the aerogel glazing windows and the increased solar gains. It should be noted that the relative share of aerogel glazing to the total window area is the same for the 24% and 33% solutions, while it is higher in the *50% aerogel* option. See Table 4.

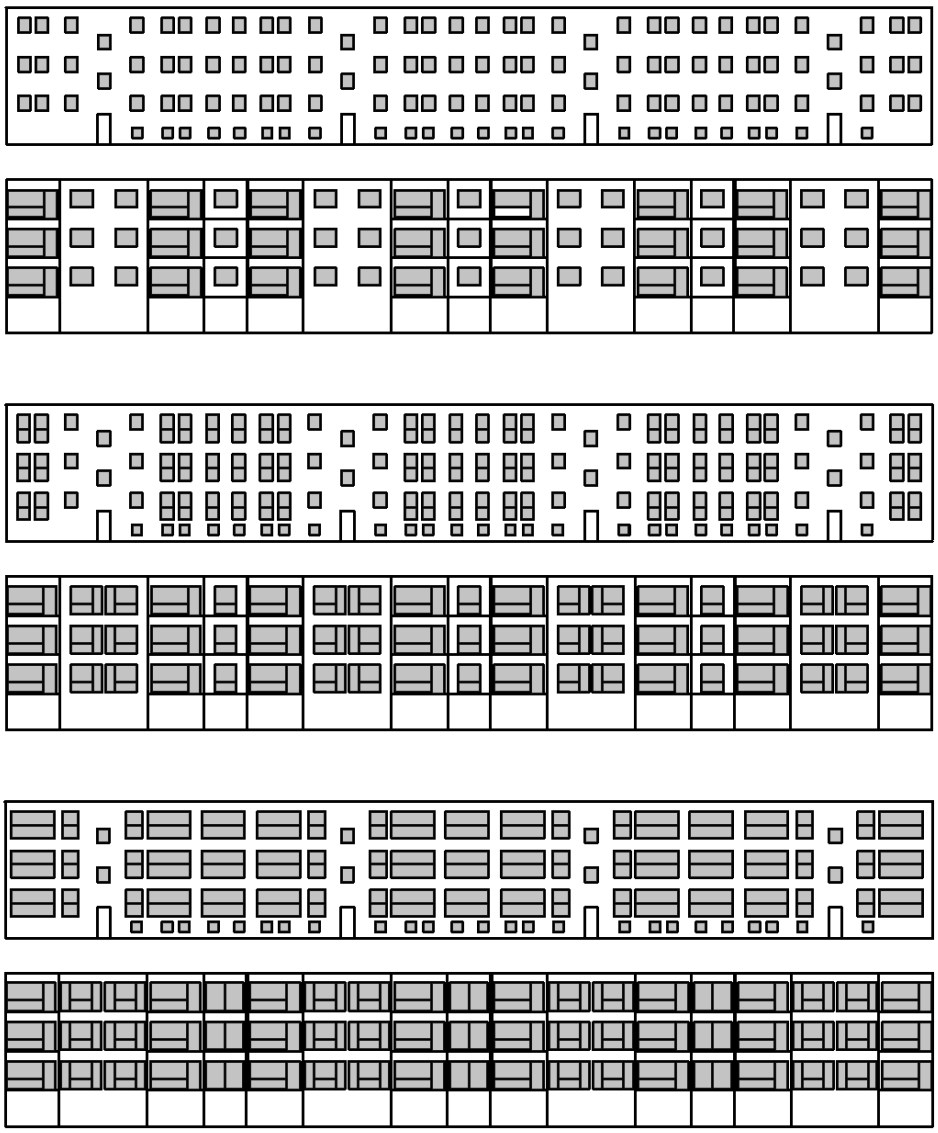

Figure 2 Illustrations of the facades of the Myhrerenga Borettslag with the different glazing alternatives. From top to bottom: East and West facades with 24%, 33% and 50% windows-to-wall ratios, respectively.

Maintenance scenarios

The $CO_{2\text{-eq}}$ emissions for the different glazing solutions are presented in Figure 4. Since the differences in emission burden between the production and end-of-life phases of the solutions with argon and aerogel glazing are very small for all the glazing ratios, the energy savings for the solutions with aerogel are still the critical factor. The *50% aerogel* alternative saves up to 7.5% of $CO_{2\text{-eq}}$ emissions in comparison to the *50% argon* alternative, which is the one performing worst. In addition, with more glazed area the embodied emissions of the production and end-of-life phases of the materials are reduced. This is due to the fact that per unit of area of façade, the glazed surface has a lower emission load than the opaque surface. When comparing the total emissions of these two phases of both *24% argon* and *50% argon*, one can see that the latter saves up to 7%. When changing the maintenance scenario to *short, medium* and *long*, the alternatives with higher glazing area still have a lower impact, and the difference in emissions between the argon and aerogel solutions are unnoticeable. However, when using the *super-short* scenario, where the substitution

rate of only the aerogel windows is doubled, the solution with aerogel is slightly higher than the solution with argon (Figure 5). In Figure 5 the composition of emissions for the proposed glazing solutions and the different maintenance scenarios is shown.

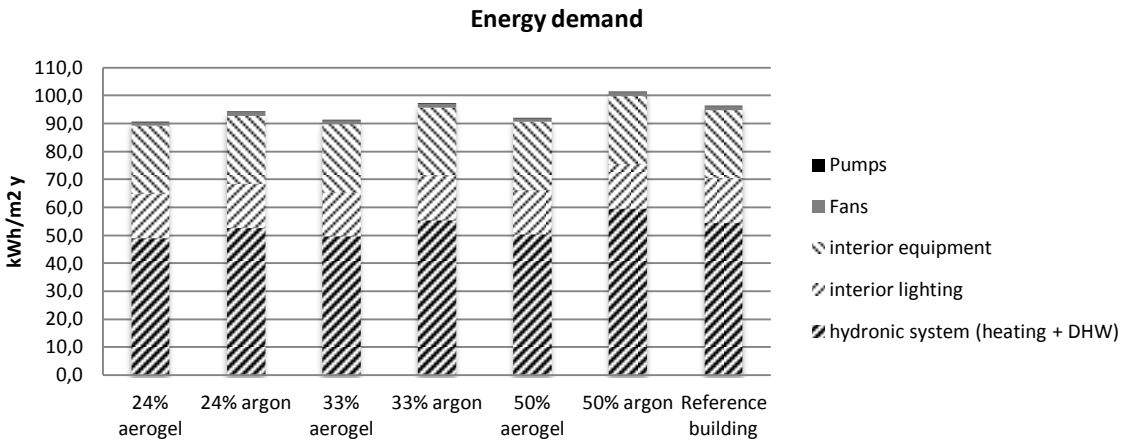

Figure 3 Energy demand for the different glazing alternatives. Values are normalized to 1m^2 of heated building area for 1 year.

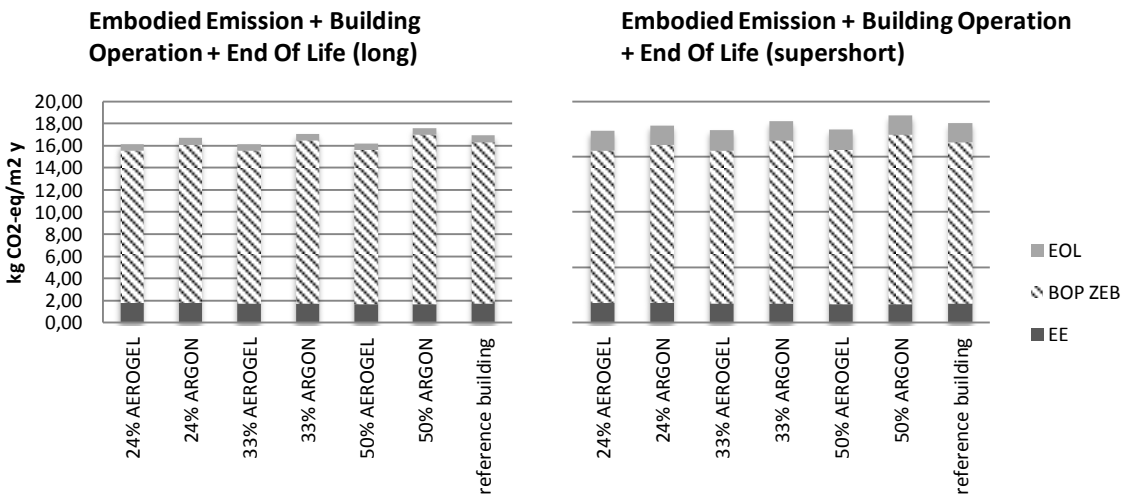

Figure 4 GHG emissions for the glazing alternatives with long and super-short maintenance intervals. Results for embodied emissions (EE), "ZEB energy mix" (BOP ZEB), and end-of-life (EOL). All values are normalized to 1 m^2 of building heated area for 1 year.

By comparing the maintenance scenarios, it becomes clear how the materials that undergo higher substitution rates have larger variation of their share of $CO_{2\text{-eq}}$ emissions. The paint and tiling share 30% and 38% of the total emission burden of the reference building for the *medium* and *short* scenarios, respectively, while the same materials share 25% and 33% of the burden for the same maintenance scenarios for the *50% argon* alternative. This explains why the solutions with smaller widows-to-wall ratios have higher emission burdens. The other factors that are varied, glass and aerogel, both have very little influence on the total $CO_{2\text{-eq}}$ emissions. In the worst-case scenario, which is represented by the *50% aerogel* solutions with the *super-short* maintenance schedule, these materials represent 14% of the total burden. For all the other maintenance scenarios the share of $CO_{2\text{-eq}}$ emissions attributed to aerogel is maximum 2%.

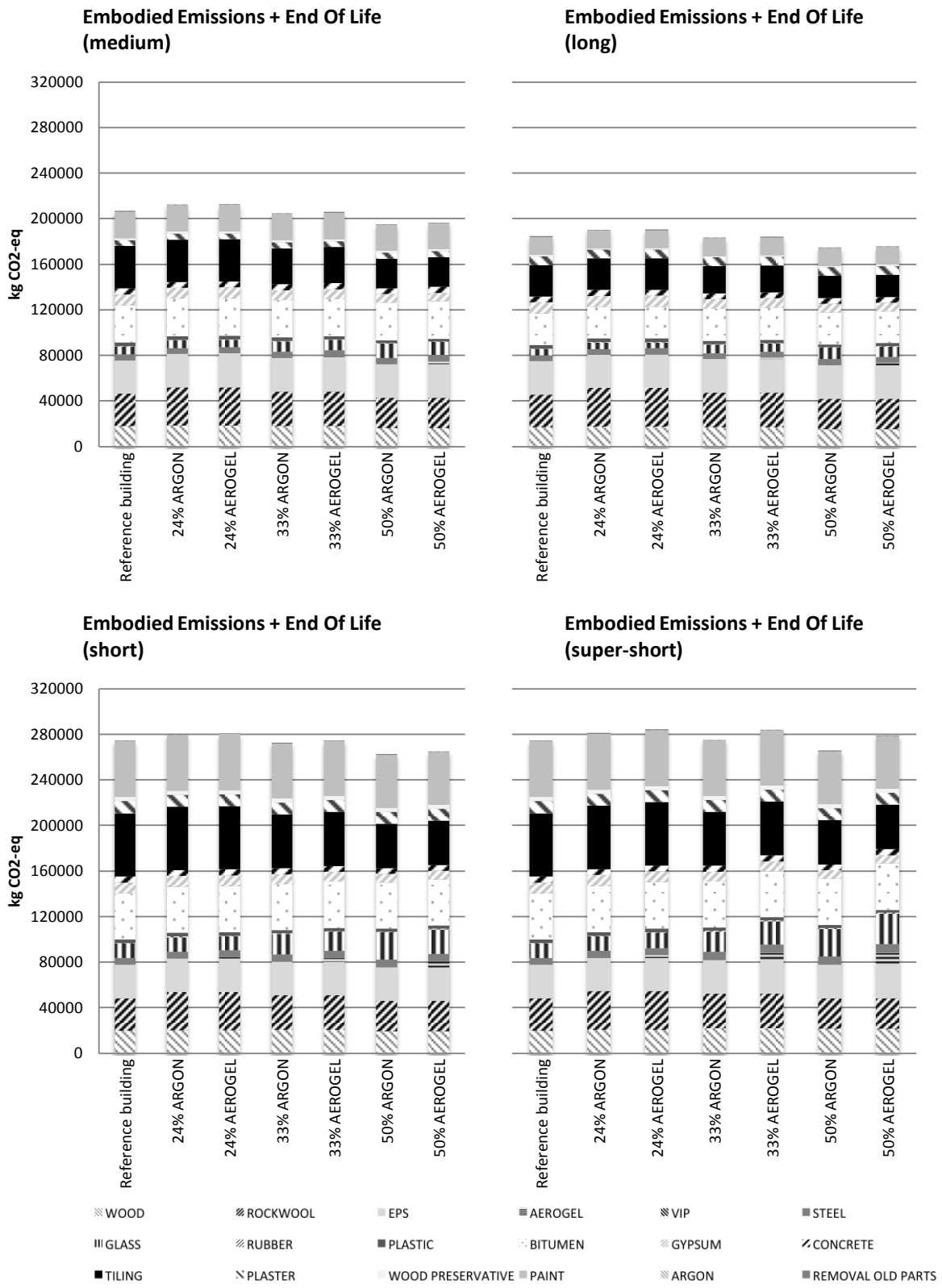

Figure 5 Composition of $CO_{2\text{-eq}}$ emissions for the different glazing solutions and different maintenance schedules. Values represent the cumulative emissions over a 50-year lifetime.

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, might be critical to the results.

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 GWP. Clearly, in addition to a higher substitution rate, this factor can be critical for determining the final environmental impact.

Information regarding GWP values of aerogel is very scarce in literature. So far, the sources that were found and investigated are for aerogel from [Aspen Aerogel, Dowson et al. 2012]. A very recent study by Dowson et al. compared the embodied $CO_{2\text{-eq}}$ emissions of Spaceloft aerogel, as claimed by Aspen Aerogel, with the $CO_{2\text{-eq}}$ emissions from the production of a lab sample at the University of Bath facilities. According to [Dowson et al. 2012] the $CO_{2\text{-eq}}$ burden 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. 2012], 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.

Information regarding the energy used to assemble the aerogel glazing is not available. For this reason, it has decided not to consider this in the calculation of the aerogel and argon insulated glazing alternatives.

Conclusions

The environmental impact of two glazing technologies applied to different façade designs and analyzed for several maintenance schedules has been compared. Results for the energy demand for a residential building located in Oslo show that the façade solutions with aerogel windows save up to 10% of yearly energy demand, in comparison to the facades equipped with triple-glazing with argon. Increasing the window-to-wall ratio from 24% to 50% raises the energy demand of the building with argon glazing by approximately 7%, while it does not noticeably affect the energy demand of the solutions equipped with aerogel glazing. Results from the greenhouse gas analysis show that the shorter the substitution rate of materials is, the greater the share of environmental impact of paint and concrete cladding becomes. This varies between 23% and 39%. On the other hand, façade designs with larger glazed surfaces benefit from a lower impact of such materials at short substitution rates. Since the glazing component has a lower impact than the opaque part per unit of façade area, a relatively smaller area of opaque wall will result in a smaller total emission burden. This trend is expected to be more dramatic if the current standard opaque insulation material, mineral wool, is substituted with a more energy-intensive material, such vacuum insulation panels. On the other hand, a substitution of the current typical external finishing by wood or some other material that has both a lower environmental impact and longer substitution rates is expected to reduce the total $CO_{2\text{-eq}}$ emission burden. Specifically for the comparison of the two glazing technologies, the amount of aerogel which is used in the glazing area, is of such a small amount that it is not noticeably counterbalancing the savings in energy demand in any of the maintenance scenarios. In conclusion, from the results presented here, the façade with aerogel glazing represents

a win-win solution, for both energy and $CO_{2\text{-eq}}$ emission savings. However, limitations to the GWP source data for aerogel require further investigation to better understand if the presented values are subject to wider variations, as may be expected.

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Reference

[WBCSD 2008] World Business Council for Sustainable Development, Energy Efficiency in Buildings full report: business realities and opportunities, WBCSD, p. 1-84 (2008)

[Uihlein and Eder 2010] Uihlein, Andreas, Eder, Peter, Policy options towards an energy efficient residential building stock in the EU-27, Energy and Buildings, 42(6), p. 791-798 (2010)

[Dodoo et al. 2011] Dodoo, Ambrose, Gustavsson, Leif, Sathre, Roger Building energy-efficiency standards in a life cycle primary energy perspective, Energy and Buildings, 43(7), p. 1589-1597 (2011)

[Fernandez and Wattersons 2011] Fernandez, Ricardo, Watterson, John, End-user GHG emissions from energy : reallocation of emissions from energy industries to end users 2005-2009, in EEA Technical report, European Environmental Agency, p. 1-104 (2011)

[Schultz and Jensen 2008] Schultz, J.M., Jensen, K.I., Evacuated aerogel glazings, Vacuum, 82(7), p. 723-729 (2008)

[Schultz et al. 2005] Schultz, J.M., et al., Super insulating aerogel glazing, Solar Energy Materials and Solar Cells, 89(2-3), p. 275-285 (2005)

[Dowson et al. 2012] Dowson, Mark, et al., Streamlined life cycle assessment of transparent silica aerogel made by supercritical drying, Applied Energy, 97(0), p. 396-404 (2012)

[Klinski and Dokka 2010] Klinski, Michael, Dokka, Tor Helge, The first apartment house renovation with Passive House components in Norway, in 14th International Passive House Conference, Dresden p. 1-6 (2010)

[Brattbakk and Thorbjørn 2004] Brattbakk, Ingar, Thorbjørn, Hansen, Post-war large housing estates in Norway - Well-kept residential areas still stigmatised?, Journal of Housing and the Built Environment, 19(3), p. 311-332 (2004)

[Statistisk Sentralbyrå 2011] Statistisk Sentralbyrå, Folke- og boligtellingen, Boliger, 19 november 2011, accessed 2012, available from: http://www.ssb.no/ (2011)

[NS 3700:2010] NS 3700:2010, Criteria for passive houses and low energy houses - Residential buildings, p. 1-80 (2010)

[NS 3031:2007] NS 3031:2007, Calculation of energy performance of buildings - Method and data, p. 1-20 (2007)

[Duer and Svendsen 1998] Duer, K., Svendsen, S., Monolithic silica aerogel in superinsulating glazings, Solar Energy, 63(4), p. 259-267 (1998)

[Rubin and Lampert 1983] Rubin, Michael, Lampert, Carl M., Transparent silica aerogels for window insulation, Solar Energy Materials, 7(4), p. 393-400 (1983)

[Hutchins and Platzer 1996] Hutchins, M.G., Platzer, W.J., The thermal performance of advanced glazing materials, Renewable Energy, 8(1–4), p. 540-545 (1996)

[Erlandsson and Borg 2003] Erlandsson, Martin, Borg, Mathias Generic LCA-methodology applicable for buildings, constructions and operation services--today practice and development needs, Building and Environment, 38(7), p. 919-938 (2003)

[Adalberth 1997a] Adalberth, K., Energy use during the life cycle of buildings: a method, Building and Environment,32(4) p. 317-320 (1997)

[Malmqvist et al. 2011] Malmqvist, Tove, et al., Life cycle assessment in buildings: The ENSLIC simplified method and guidelines, Energy, 36(4), p. 1900-1907 (2011)

[Kellemberg and Althaus 2009] Kellenberger, Daniel, Althaus Hans-Jorg, Relevance of simplifications in LCA of building components, Building and Environment, 44(4), p. 818-825 (2009)

[Citherlet and Defaux 2007] Citherlet, Stephane, Defaux, T., Energy and environmental comparison of three variants of a family house during its whole life span, Building and Environment, 42(2), p. 591-598 (2007)

[Blengini 2009] Blengini, Gian Andrea, Life cycle of buildings, demolition and recycling potential: A case study in Turin, Italy, Building and Environment, 44(2), p. 319-330 (2009)

[Gustavsson et al. 2010] Gustavsson, Leif, et al., Life cycle primary energy use and carbon emission of an eight-storey wood-framed apartment building, Energy and Buildings, 42(2), p. 230-242 (2010)

[Adalberth 1997b] Adalberth, K., Energy use during the life cycle of single-unit dwellings: Examples, Building and Environment, 32(4) p. 321-329 (1997)

[NHP2 2007] Nasjonal handlingsplan for bygg- og anleggs-avfall 2007 - 2012, NHP2, (2007)

[Blom et al. 2010] Blom, Inge, et al., Environmental impact of dwellings in use: Maintenance of facade components, Building and Environment, 45(11), p. 2526-2538 (2010)

[Bohne et al. 2008] Bohne, R.A., et al., Dynamic eco-efficiency projections for construction and demolition waste recycling strategies at the city level, Journal of Industrial Ecology, 12(1), p. 52-68 (2008)

[Blengini and Di Carlo 2010] Blengini, Gian Andrea, Di Carlo, Tiziana, The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings, Energy and Buildings, 42(6), p. 869-880 (2010)

[Chen et al. 2001] Chen, T.Y., et al., Analysis of embodied energy use in the residential building of Hong Kong, Energy, 26(4), p. 323-340 (2001)

[Bergsdal et al. 2007] Bergsdal, Håvar, et al., Dynamic material flow analysis for Norway's dwelling stock, Building Research and Information, 35(5), p. 557-570 (2007)

[Sartori et al. 2008] Sartori, Igor, et al., Towards modelling of construction, renovation and demolition activities: Norway’s dwelling stock,1900-2100, BUILDING RESEARCH & INFORMATION, 36(5), p. 416-425 (2008)

[Byggforskserien 2010] Intervaller for vedlikehold og utskifting av bygningsdeler, in Byggforskserien p. 1-12 (2010)

[Ecoinvent 2010] Ecoinvent, Ecoinvent Data v2.2, Swiss centre for Life Cycle Inventories (2010)

[Aspen Aerogel] Aspen Aerogel, Space Loft insulation, available from: http://www.aerogel.com/, accessed 2012.

[Dokka 2011] Dokka, Tor Helge, Proposal for CO2-factor for electricity and outline of a full ZEB-definition, The Research Centre on Zero Emission Buildings, p. 1-7 (2011)