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Aerogel vs. argon insulation in windows: a greenhouse gas emissions analysis

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Abstract

The scope of this study is a comprehensive analysis of the greenhouse gas emissions from the partial substitution of triple-glazing units with argon gas (U-value of 0.79 W/m^2 K) with double-glazing units with either monolithic aerogel (U-value of 0.65 W/m^2 K) or granular aerogel (U-value of 0.31 W/m^2 K).

A residential building located near Oslo and fully upgraded with passive house solutions is used as a case study for this analysis. A cradle-to-site analysis is performed on the facade components. Two replacement schedules and three window-to-wall ratios are used to evaluate the differences in total emissions. Sensitivity analyses based on increasing the fraction of the aerogel glazing, varying the greenhouse gas emissions of the aerogel production, and changing the service life of the aerogel glazing are also performed.

Results show that both the options with windows with aerogel are effective in reducing the greenhouse gas emissions, regardless of the total window-to-wall ratio and the replacement schedule used. By increasing the share of the aerogel glazing, the savings in emissions increase from 5% to 9%. The sensitivity analysis shows that the greenhouse gas emissions from the production of aerogel should be at least 8 times higher than those currently reported to totally counterbalance the achieved energy savings.

Keywords: greenhouse gas emissions; granular aerogel; monolithic aerogel; energy retrofitting; windows.

1. Introduction

Both the building industry and the building stock are energy-intensive sectors and cause significant greenhouse gas 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 several sources [1-3] the building sector in the EU accounts for about 40% of total primary energy use and for about 25% of greenhouse gas emissions [4]. This refers to the energy used during their operation phase. To follow the path of the Kyoto Protocol, several European countries have adopted various measures and regulations that address energy-saving strategies in the building sector.

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 low-energy coatings and argon gas filling, for instance, represent an effective energy-saving solution. However, these technologies have the drawback that they drastically reduce the amount of solar radiation that passes through the glass due to use of several coated layers. This condition can be favourable at medium latitudes (such as in central Europe) where there is ample solar radiation in 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 an insulation value higher than that of classic triple and quadruple glazing solutions. Products available today in the market [5] can provide a stunning 0.3 W/m^2 K (for the centre glazing U-value) but at the sacrifice of losing visible and solar transmittance. Glazed products with granular aerogel are made of two 4-mm thick glass panes and a cavity filled with a layer of granular aerogel of variable thicknesses [5]. On the other hand, recent studies have demonstrated that, by taking advantage of the optical properties of aerogel, it is possible to produce double-glazed windows that not only have a very low U-value but also have a visible transmittance higher than that of the correspondingly standard alternative [6, 7]. Simulations of the energy consumption of a single family house insulated according to the passive house standard showed that the option with glazing units with monolithic aerogel gives a 19% energy savings compared to the use of triple-glazed units with low-e coatings and argon gas filling [6]. Glazed prototypes with monolithic aerogel consist in two 4-mm thick glass panes and a vacuumed gap filled with a 13.5-mm thick layer of monolithic aerogel [6]. Several studies [6-11] show that windows insulated with aerogel, either granular or monolithic, represent a promising solution to achieve high insulation levels and reduce the total greenhouse gas emissions. On the other hand, aerogel has higher CO_2 emissions per kg for production than those required for argon [12, 13]. It is interesting, then, to investigate to which extent the energy savings given by using aerogel as an insulating material for windows are counterbalanced by the disadvantages given by the higher greenhouse gas emissions of the aerogel production.

2. Objective

The objective of the work is to compare and assess the greenhouse gas emissions of three different glazing technologies applied in the energy retrofitting of a housing complex located near Oslo, Norway. Results from the calculations of the annual energy use and greenhouse gas emissions of several alternative combinations of windows technologies, window-to-wall ratios, and replacement schedules are presented. Additionally, sensitivity analyses on increasing the share of the windows insulated with aerogel, the variation of the emissions of the aerogel production, and the variation of the service life of aerogel glazing are performed. Results from the calculation of the annual energy use and the greenhouse gas emissions performed in the sensitivity analyses are also presented.

3. Method

3.1. The case study

An apartment building near Oslo, Norway, the Myhrerenga Borettslag (a housing cooperative), is used as a case study in the energy and greenhouse gas analysis. Conforming to the building trend of post-war decades, the Myhrerenga Housing Cooperative represents one of several examples of residential buildings that have shaped the urban landscape of most Norwegian towns and currently account for approximately 23% of the entire Norwegian dwelling stock [14]. The building is approximately 65 m long and 10 m wide and has 24 apartments divided in eight units per floor plus a basement. The apartments, which face both East and West, vary from 54 m^2 to 68 m^2 in size and are served by four stairwells positioned on the East side of the building. There are partially enclosed balconies on the West façade. The facades consist of a timber frame with mineral wool insulation. The load bearing structure consists of concrete walls that run orthogonally from the East façade to the West façade [15]. Such a structural system allows a high degree of modification of the openings placed on the East and West facades, as it is proposed in this study (Fig. 1). The apartment building was renovated in 2010, and a description of the upgrading design is to be found in [16]. In the performed renovation of the building an additional layer of 200 mm of mineral wool was placed externally to the facades of the buildings [16]. In this study, however, the addition of an external layer of 250 mm of mineral wool is considered for all the facades. This results in an after-retrofitting U-value of the external walls of 0.10 W/m^2 K. A description of the layers of the retrofitted facades according to this study is shown in Table 1. Table 2 lists the materials used in the renovation of the building (excluding the facades), the layers thickness, the materials service lives, and the transportation distances.

The variation of the window-to-wall ratios aims at studying to what extent the ratio of the glazed surfaces to the opaque surfaces influences the building energy use for heating for an apartment building located near Oslo. In a well-insulated building, windows are the components of the building envelope where most of the heat losses and gains occur, and it is interesting to evaluate the drawbacks of a large glazed area in terms of energy use for space heating. Table 3 shows the values of the window-to-wall ratios used in this work. The 0.24 glazing ratio is the value of all the current facades of the Myhrerenga Borettslag. The 0.50 glazing ratio is set as the maximum value, since larger fenestration areas would have compromised the availability of wall surfaces for placing furniture and domestic appliances. The 0.33 glazing ratio has been set as an intermediate value between the two above.

3.2. Glazing alternatives

The variation of the fraction of the aerogel glazing of the total number of windows aims at understanding the full potential of the employment of such technologies in residential buildings, in terms of both energy savings and greenhouse gas emissions abatement. The quantities of windows with aerogel are shown as percentages in Table 3. The alternatives named "standard" (with the *_s* suffix) have an increasing portion of windows with aerogel for an increasing total window-to-wall ratio. On the other hand, the alternatives named "full" (with the *_f* suffix) have the same portion of windows with aerogel regardless of the total window-to-wall ratio. In this last case, the small number of windows with argon in the "full" aerogel alternatives refers to the windows used in the basement walls, which are not considered in the analyses but still contribute to the building energy use and greenhouse gas emissions.

The variation of the replacement schedule, which determines when a product has reached the end of its service life, aims at studying to what extent a shorter service life of the aerogel glazing influences the total building greenhouse gas emissions. The maintenance schedules of the windows and the other building components used in this work are extracted from [17]. As above mentioned, the thermal insulation of the windows with monolithic aerogel is achieved by both vacuuming the gap between the two glass panes and filling it with monolithic aerogel, which has a very low tensile strength [18] and is a very fragile material. It is assumed, then, that the service life of such windows cannot compare to that of standard triple-glazed-with-argon units. However, specific information on the service life of windows with monolithic aerogel has not been found in literature. It has been decided then to use a service life that is half of the triple-glazed units, as a base case. To present coherent results between the two glazing products with aerogel, their service life has been set the same. The values of the replacement schedules of the different glazing technologies are shown in Table 4. It is worth noticing that the service life of the triple-glazed units with argon varies between 60 years for the long maintenance schedule and 20 years for the short maintenance schedule. The service life of the double-glazed units with aerogel insulation varies between 30 years for the long maintenance schedule and 10 years for the short maintenance schedule. Since the building service life is 50 years, the service life of the triple-glazed units with argon is limited to 50 years by the building service life.

The variation of the greenhouse gas emissions for the production of aerogel aims at understanding to what extent the energy savings given by the application of such a material in windows are penalized by the greenhouse gas emission from the aerogel production. The greenhouse gas emissions value for the production of aerogel used in this study (4.2 kg $CO_{2\text{-eq}}$ /kg) is taken from [13]. However, as found by Dowson *et al.* [12], such a value is subject to a large variation (up to 23 times), due to the type of the production process and the efficiency of the production system used. In such a perspective, since there is little information on the emissions from the aerogel production, such a sensitivity analysis will give a deeper insight on the environmental advantages or disadvantages of using these windows technologies.

Finally, the variation of the service life of the aerogel glazing aims at filling the lack of knowledge in the literature. In this analysis, the service life of these windows is set equal to the service life of the argon glazing for the short maintenance schedule (which is 20 years, as shown in Table 4). It is then gradually reduced to 2.5 years. In such a perspective, the effect on the building lifecycle emissions of a longer or a shorter service life of aerogel glazing can be evaluated.

The starting point is a total window-to-wall ratio of 0.24, which represents the current appearance of the Myhrerenga Borettslag (Fig. 1). Increasing the window-to-wall ratio only involves the facades of the three floors with apartments, as shown in Fig. 1. The number of windows placed on the basement walls is therefore left unchanged. The characteristics of the windows with granular and monolithic aerogel, and their solar and visible spectral average values are extracted from Buratti and Moretti [19, 20]. The thermal transmittance of granular aerogel is 13.5 mW/m K [11] and the thermal transmittance of the vacuumed monolithic aerogel is 11 mW/m K [21]. The windows centre U-values and solar heat gain coefficients of the double-glazed units with either monolithic or granular aerogel used in this study (shown in Table 5) are consistent with other values found in literature [6-11, 19-27]. All windows are assumed to have timber frames. The thermal losses through the timber windows frames are not considered in this study, as different window-to-wall ratios are obtained by different configurations of windows size and shape. In such a perspective, by including the thermal losses through the windows frame, a comparison between the different alternatives would have been difficult.

3.3. Energy model

A thorough description of the simplifications and values used in the modelling of both the energy and the LCA models is to be found in [15]. Only 12 out of the total 24 apartments are geometrically described in the energy model (shown in purple in Fig. 2). The remaining 12 apartments are modelled as adiabatic zones. The basement (shown in cyan) and the four stairwells (shown in blue) are modelled as unheated thermal zones. A detailed description of the energy model is found in [15]. The total gross conditioned area of the 24 apartments is approximately 1580 m^2, and the total exposed wall area of the 24 apartments is approximately 4750 m^2. The indoor environmental controls and variables have been set according to the Norwegian Standards NS 3700 and NS 3031 [28, 29]. Calculations are performed using EnergyPlus [30] and results produced include delivered annual energy for heating, ventilation fans, water pumps, electric appliances, lighting appliances, heat pumps, and domestic hot water. The heating system is modelled as a single air-to-water heat pump. The only energy source of the building is, therefore, electricity. The results are normalized to 1m^2 of building conditioned area.

3.4. LCA model

The calculation of the greenhouse gas emissions of the building components is based on the phases of material production and transportation to the building site [31]. The CO_2 emissions from the disposal and waste management of the building components are not included in the model. This is due to the limited information on the disposal strategies for aerogel. Substitution of building components is considered in the LCA model and the information on the two maintenance schedule scenarios used in the model is found in [17]. In such a perspective, the emissions calculation is based on a cradle-to-site LCA model (phases A1-A4, B2, B4, and B6 according to the EN 15804:2012). The retrofitted building lifetime is set to 50 years, according to the studies by Bergsdal *et al.* [32] and Sartori *et al.* [33]. Data on the emissions of the materials used in the retrofitting of the test building is extracted from the Ecoinvent database version 2.2 [34], and for aerogel is given by [12, 13]. The emissions for production of aerogel and argon used in this study are 4.20 kg$CO_{2\text{-eq}}$/kg and 0.18 kg$CO_{2\text{-eq}}$/kg respectively. A sensitivity analysis is performed on the emissions of the production of aerogel by setting a starting value of 0.20 kg$CO_{2\text{-eq}}$/kg. The conversion factor from electricity grid power (kWh) to kg$CO_{2\text{-eq}}$ is calculated for the European electricity mix (0.361 kg$CO_{2\text{-eq}}$/kWh) [35].

4. Results

4.1. Energy results

Fig. 3 shows the annual building energy use normalized to 1 m^2 of building heated area. The energy uses for domestic hot water (DHW), fans, pumps, lights, and equipment, are the same for all the glazing alternatives. The energy use for space heating varies from 16 kWh/m^2 y for the alternative with 0.24 glazing ratio and monolithic aerogel (*24_m_aer_s*) to 18 kWh/m^2 y for the alternative with 0.24 glazing ratio and argon (*24_arg*), and from 20 kWh/m^2 y for the alternative with 0.50 glazing ratio and monolithic aerogel (*50_m_aer_s*) to 25.4 kWh/m^2 y for the alternative with 0.50 glazing ratio and argon (*50_arg*). The differences between the alternatives with granular aerogel and monolithic aerogel are less than 0.5 kWh/m^2 y. These results are explained by the different solar heat gain coefficients and U-values of these two alternatives. The double-glazed units with monolithic aerogel have the highest solar heat gain coefficient (0.74) and a U-value (0.65 W/m^2 K) that is higher than that of the glazing with granular aerogel and lower than that of the triple-glazing with argon. On the contrary, the window alternatives with granular aerogel have the lowest solar heat gain coefficient (0.31) and the lowest insulation value (0.44 W/m^2 K). In such a perspective, the low solar heat gain coefficient of the unit with granular aerogel is compensated by its high U-value. It is worth remembering that the windows with aerogel (either granular or monolithic) are just a fraction of the total window area. By increasing the fraction of windows with aerogel, the difference between the two glazing types is expected to increase, as it will be discussed later in this paper. The alternative with triple-glazed units with argon and glazing ratio of 0.24 has an energy use for space heating which is 2 kWh/m^2 y higher than that of the alternative with same glazing ratio and double-glazed units with monolithic aerogel. This difference increases to 3 kWh/m^2 y for the alternatives with glazing ratio of 0.33, and to 5 kWh/m^2 y for the alternatives with glazing ratio of 0.50. In such a perspective, the use of the monolithic aerogel saves up to 20% of the energy use for space heating. A similar energy saving is found when the granular aerogel is used. This means that by increasing the glazing ratio and using windows with aerogel the energy use for space heating increases less than when standard windows with argon are used. Table 6 summarizes the savings of building energy use given by the use of aerogel-insulated windows.

4.2. Greenhouse gas analysis

Fig. 4 shows the annual greenhouse gas emissions per square meter of heated floor area of the different glazing alternatives calculated for a short replacement schedule. The service life is 20 years for the windows with argon, and 10 years for the windows with either granular or monolithic aerogel, as shown in Table 4. It is worth remembering that the calculation of the emissions is limited to the phases of material production and transportation to the building site. The result is largely dominated by the emissions of the building energy use (named *Op* in Fig. 4). This is because the average European electricity mix is used for the electricity-to-emissions conversion factor, which credits 0.361 kg $CO_{2\text{-eq}}$ per each kWh of delivered electricity to the operation of the building, and because the mass of the produced materials is very small in comparison to the mass of the whole building construction. The emissions for the material production phase (named *EE* in Fig. 4) never exceed 5% of the total, and the emissions for the replacement of the building components (named *Ma* in Fig. 4) never exceed 4% of the total. Consequently, the difference in emissions of both the material production and maintenance phases between the alternatives with argon glazing and aerogel glazing is very little and never exceed 1.5% of the total. Part of the higher emissions given by the use of aerogel is compensated by the smaller number of glass panes in the windows (2 for the windows with aerogel and 3 for the windows with argon). In such a perspective, the energy savings given by the use of aerogel in windows outweigh the disadvantages of its higher embodied emissions and a shorter service life. It is worth noting that the emissions given by the transportation to the building site are higher for the aerogel glazing (which are supposed to be produced outside Norway) than those for the argon glazing (which are produced nearby the building site). However, the calculation of the emissions for all the materials used in this study (with the exception of aerogel) is based on the Ecoinvent database. This does not reflect the specific country electricity-to-emissions conversion factors for the material production, which may give different results if taken into consideration.

Fig. 5 shows the annual greenhouse gas emissions per square meter of heated floor area of the different glazing alternatives calculated for a long maintenance schedule. By increasing the service life of the building components, the fraction of emissions due to the maintenance phase decreases to less than 1% of the total emissions. In such a perspective, the result is largely dominated by the emissions given by the building energy use. The alternative with granular aerogel and 0.50 glazing ratio has approximately 6% lower total emissions than those of the alternative with argon and the same glazing ratio. The same value is found when comparing the total building energy use of the above-described alternatives, as shown in Fig. 3. In such a perspective, by increasing the maintenance schedule of the building components, the embodied emissions of the maintenance phases influence very little the total lifecycle emissions. Consequently, the choice of any of the windows types does not give very different embodied emissions.

Fig. 6 and 7 show the total embodied emissions due to the phases of material production and maintenance, calculated for the short and long maintenance schedules respectively. The *Façade:walls* entry only refers to the materials used in the retrofitting of the opaque surfaces of the external facades (in Table 1). The *Façade:windows* entry only refers to the materials used for the windows (in Table 4). The other building parts (balconies, roof, and basement) do not have changes in emissions due to the use of the different window technologies or glazing ratios, and their emissions are only shown for comparison (in Table 2). As shown in Fig. 6, by increasing the glazing ratio from 0.24 to 0.50 the total emissions of the alternative with triple-glazing-with-argon units decrease. The emissions of the opaque wall surfaces decrease from approximately 121 t $CO_{2\text{-eq}}$ to 90 t $CO_{2\text{-eq}}$, while the emissions of the windows increase from

25 to 41 t $CO_{2\text{-eq}}$. This means that when the windows with argon are used and the lifecycle emissions are calculated for a short maintenance schedule the emissions per m^2 of the opaque part of the external wall are higher than those of the glazed part. This is because concrete slates, which have high embodied greenhouse gas emissions, are used for the external finishing layer of the building, as shown in Table 1. However, this is not the case when windows with either granular or monolithic aerogel are used. The emissions of 1 m^2 of aerogel glazing are slightly higher than those of 1 m^2 of opaque wall, as shown in Fig. 6. The total lifecycle emissions of the alternative named *24_aer_g_s* are 225.6 t $CO_{2\text{-eq}}$, and are 229.9 t $CO_{2\text{-eq}}$ for the alternative named *50_aer_g_s*. The alternative with granular aerogel and 0.50 glazing ratio has approximately 5 t $CO_{2\text{-eq}}$ more than the counterpart with monolithic aerogel (due to the higher thickness of the granular aerogel layer), and 35 t $CO_{2\text{-eq}}$ more than the alternative with windows with argon and the same glazing ratio. In addition, the emissions accounted for in the double-glazing units with granular aerogel are 33% of the total embodied emissions. On the other hand, the emissions accounted for in the triple-glazing units with argon are less than 20% of the total embodied emissions for the alternative with 0.50 glazing ratio.

When the long maintenance schedule is used, the differences in total embodied emissions between the different glazing alternatives decrease, as shown in Fig. 7. In addition, the total embodied emissions of the alternatives with either aerogel or argon decrease when the glazing ratio increases. This means that when the long maintenance schedule is used the embodied emissions (per m^2 of façade area) of the windows (either with argon or aerogel) are lower than those of the opaque surface of the external walls. The embodied emissions of the windows with granular aerogel of the alternative with 0.50 glazing ratio are 1 t $CO_{2\text{-eq}}$ higher than those of the windows with monolithic aerogel and the same glazing ratio, and are 10 t $CO_{2\text{-eq}}$ higher than those of the windows with argon and the same glazing ratio. The embodied emissions of the double-glazed units with monolithic aerogel are 18% of the total embodied emissions. The total embodied emissions of the alternative with monolithic aerogel and 0.50 glazing ratio calculated for the long maintenance schedule are 75 t $CO_{2\text{-eq}}$ lower than those of the same glazing alternative calculated with the short maintenance schedule. This is 1/3 less total embodied emissions. Both Fig. 6 and 7 show that by increasing the glazing ratio there is no strong increment of embodied emissions (Fig. 6). This means that the increase of the total lifecycle emissions shown in Fig. 4 and 5 is only due to the raising energy use for space heating. However, it is interesting to note that there is a high potential for reduction of embodied emissions in the alternatives with aerogel, as these window types take a high fraction of the total embodied emissions, as shown in Fig. 6.

4.3. Sensitivity analysis: variation of the fraction of aerogel windows

Fig. 8 shows the annual building energy use of the different glazing alternatives and glazing ratio. The fraction of the windows with either granular or monolithic aerogel covers at least 96% of the total glazed surface (as described in Table 3). These are named with the suffixes *g_aer_f* or *m_aer_f*, to be distinguished from the previously analysed alternatives. The energy use for space heating varies from 10 kWh/m^2 y, for the alternative with granular aerogel and 0.24 glazing ratio, to 13 kWh/m^2 y, for the same glazing alternative and 0.50 glazing ratio. In comparison, the use of monolithic aerogel gives 0.5 kWh/m^2 y higher energy use for space heating in the alternative with 0.24 glazing ratio, and 1.5 kWh/m^2 y higher energy use in the alternative with 0.50 glazing ratio. This means that, when comparing the two types of aerogel glazing and increasing the glazing ratio, the high solar heat gain coefficient of the monolithic aerogel does not compensate its lower insulation value. The difference in energy use for space heating between the alternatives with argon and the alternatives with aerogel increases considerably when the glazing ratio increases. Moreover, by increasing the glazing ratio from 0.24 to 0.50 the energy use for space heating increases by 20% when granular aerogel is used, and 30% when argon is used. The substitution of windows with argon with windows with granular aerogel saves almost 50% of energy use for space heating, for the alternative with 0.50 glazing ratio. The results are summarized in table 6.

Fig. 9 shows the total lifecycle emission of the different glazing alternative normalized to 1 m^2 of heated floor area and calculated for the short maintenance schedule. When the fraction of aerogel glazing is set to 98% of the total windows (as the windows in the basement are triple-glazed units with argon), the phases of material production and substitution of components (*EE* and *Ma* in Fig. 9) accounts for approximately 12% of the total emissions, due to the higher amount of aerogel. The emissions of these two phases were 9% of the total emissions in the previous case, as shown in Fig. 4. However, the high energy savings given by the larger use of windows with aerogel well outweigh the increased embodied emissions, as shown in Fig. 9. This is due to the fact that most of the emissions (up to 88% of the total) are still given by the building energy use. The alternatives with either granular or monolithic aerogel and 0.50 glazing ratio have approximately 13% less total lifecycle emissions than the counterpart with argon and same glazing ratio. This difference was less than 6% in the alternative with a lower fraction of windows with aerogel and the same glazing ratio (as shown in Fig. 4). In such a perspective, by increasing the fraction of aerogel glazing increases the savings in lifecycle emissions.

Fig. 10 shows the composition of the embodied emissions of the different glazing alternatives and glazing ratios calculated for the short maintenance schedule. The fraction of embodied emissions credited to the windows with aerogel varies between 26% and 43% of the total building lifecycle embodied emissions. In the case of the alternatives with the highest glazing ratio, the embodied emissions of the double-glazed units with aerogel are approximately 1.25 times higher than those of the opaque surface of the external walls. The embodied emissions are approximately 2.75 higher than those of the triple-glazed units with argon, for the alternative with 0.50 glazing ratio. The difference in embodied emissions between the windows with granular or monolithic aerogel is 12 t $CO_{2\text{-eq}}$ for the alternatives with 0.5 glazing ratio (this was 5 t $CO_{2\text{-eq}}$ in Fig. 6). Fig. 10 shows that even if the embodied emissions of the alternatives with aerogel are much higher than those of the alternative with argon for a high glazing ratio, these have lower lifecycle emissions, due to lower energy use for space heating. In such a perspective, higher savings could be achieved if the emissions for the production of aerogel would diminish, or the service life of these types of window would increase, as investigated in the following sections.

4.4. Sensitivity analysis: variation of emissions of aerogel production

Fig. 11, 12, and 13 show the variation of the building lifecycle emissions of the different glazing alternatives and glazing ratio when the emissions of aerogel production varies, calculated for a short maintenance schedule. These scenarios aim at understanding what happens to the total building lifecycle emissions if the emissions of production of aerogel increase or decrease, and when these balance those of the corresponding alternatives with argon. The dashed line represents the building lifecycle emissions of the alternative with argon and corresponding glazing ratio. The marked black and grey lines represent the increasing lifecycle emissions of the alternatives with aerogel when its emissions for production increase. When the lifecycle emissions of the alternatives with aerogel glazing meet the lifecycle emissions of the alternative with argon glazing at the right end of the horizontal axis (high emissions for the production of aerogel), it means that a better thermal performance (heat losses vs. heat gains) is achieved for the aerogel glazing than that of the argon glazing. The value of 0.2 kg $CO_{2\text{-eq}}$/kg is close to the emissions used for the production of argon. The value of 4.2 kg $CO_{2\text{-eq}}$/kg is the one used in the previously shown results and found in the literature.

As shown in Fig. 11, the lifecycle emissions of the alternative with argon glazing and 0.24 glazing ratio are balanced by a value for the aerogel production between 35 kg $CO_{2\text{-eq}}$/kg (alternative named *24_g_aer_s*) and 89 kg $CO_{2\text{-eq}}$/kg (alternative named *24_m_aer_f*). In such a perspective, the use of a larger number of windows with monolithic aerogel gives the best result for this glazing ratio. Interestingly, for a value of approximately 7 kg $CO_{2\text{-eq}}$/kg the two "full" alternatives with granular or monolithic aerogel perform equally. Below that value, the use of monolithic aerogel gives slightly lower lifecycle emissions, while above that value the alternative with granular aerogel performs better. Therefore, the two alternatives with granular aerogel balance the lifecycle emissions of the counterpart with argon for higher emissions values than those of the two alternatives with monolithic aerogel. On the other hand, the reduction of emissions of production of aerogel does not give significant improvement in the total lifecycle emissions. This is due to the low glazing ratio of the 0.24 alternatives.

As shown in Fig. 12, when the glazing ratio increases to 0.33, the emissions of aerogel production needed for balancing the lifecycle emissions of the alternative with argon glazing decrease to approximately 46 kg $CO_{2\text{-eq}}$/kg (alternative named *33_g_aer_f*), and to 75 kg $CO_{2\text{-eq}}$/kg (alternative named *33_m_aer_f*). As seen previously, the alternative with "full" granular aerogel has lower lifecycle emissions than those of the alternative with "full" monolithic aerogel when the aerogel emissions are lower than 10 kg $CO_{2\text{-eq}}$/kg. The two alternatives with low fraction of windows with aerogel meet the lifecycle emissions of the counterpart with argon glazing for values of aerogel emissions that are very close to the ones needed by the "full" alternatives. By decreasing the emissions for the aerogel production to 0.2 kg $CO_{2\text{-eq}}$/kg gives less than 0.5 kg $CO_{2\text{-eq}}/m^2$ y savings for the two "full" alternatives (grey lines in Fig. 11).

As shown in Fig. 13, when the glazing ratio is raised to 0.50, the alternative with high number of windows with monolithic aerogel (named *50_m_aer_f*) is outperformed by the alternative with low number of windows with monolithic aerogel (named *50_m_aer_s*) when the emissions for the aerogel production are higher than 70 kg $CO_{2\text{-eq}}$/kg. This means that by increasing the glazing ratio, the embodied emissions given by the alternative with "full" monolithic aerogel are higher than the emissions saved by the use of large areas of monolithic aerogel. This result can be compared to Fig. 12, when the alternatives with "standard" and "full" number of monolithic aerogel glazing meet the horizontal dashed line (*33_arg*) for a value of emissions of aerogel production of approximately 75 kg $CO_{2\text{-eq}}$/kg. As mentioned above, the building lifecycle emissions are dominated by the emissions due to the building energy use. The windows with monolithic aerogel in the "full" alternative with 0.50 glazing ratio have embodied emissions that are less than 1.5 kg $CO_{2\text{-eq}}/m^2$ y, when these are calculated for the short maintenance schedule. In comparison, the emissions due to the building energy use of the same alternative are 30 kg $CO_{2\text{-eq}}/m^2$ y. In such a perspective, by reducing the emissions of the production of aerogel would result in marginal lifecycle emissions abatement. On the other hand, by using a "greener" electricity-to-emissions factor, this reduction would have a greater impact.

4.5. Sensitivity analysis: variation of maintenance schedule

Fig.14 shows the variation of the maintenance schedule of the different glazing alternatives with either monolithic or granular aerogel, and different glazing ratios. The different maintenance schedules are represented as decreasing service life of windows, from a 20-year to a 2.5-year service life. The service life of the three glazing alternatives with argon is 20 years (short maintenance schedule, as set in Table 4), and these are represented as either dashed or dotted lines. The service life of the other building components used in the energy retrofitting is not changed and is set for a short maintenance schedule (Tables 1 and 2).

By reducing the service life of windows with aerogel, the building lifecycle emissions increase. The difference in emissions between the highest and the lowest service lives is strongest in the alternatives with the highest fraction of windows with aerogel. This is because the service life of the argon glazing does not change. The alternatives with 0.24 glazing ratio balance the lifecycle emissions of the counterpart with argon when the components service life is between 3 and 5 years, depending on the type of aerogel used and the fraction of windows with aerogel. The alternatives with 0.33 glazing ratio meet the lifecycle emissions of the alternative with argon when the service life is between 4 and 5 years. The alternatives with 0.50 glazing ratio meet the lifecycle emissions of the alternative with argon when the service life is between 3 and 4 years. The savings in emissions given by increasing the windows service life from 10 to 20 years are less than 1 kg $CO_{2\text{-eq}}/m^2$ y, for the alternatives with the highest fraction of windows with aerogel. These decrease to less than 0.5 kg $CO_{2\text{-eq}}/m^2$ y for the other glazing alternatives. In such a perspective, by doubling the service life of the double-glazed units with aerogel results in lower lifecycle emissions than those achieved by decreasing the emissions of the production of aerogel by 21 times. This is due to the emissions saved by reducing the production of all the other components of the window (such as glass).

5. Limitations

There are several limitations in this study that might affect the results of energy use and lifecycle emissions. These limitations are discussed in this section.

The calculation of the annual building energy use has only been performed for one orientation of the building, which has the longitudinal axis roughly aligned to a North-South orientation. Different building orientations might give different results for the energy use. However, as found by Persson *et al.* [36], the different orientation of a large glazing in a terraced house in Gothenburg does not significantly influence the building heating demand. In the case of the Myhrerenga Borettslag, an East-West orientation would result in having a south facing façade, which is expected to compensate for the thermal losses of the opposite north facing façade. Alternatives with different combinations of glazing with monolithic and granular aerogel have not been considered in this study. Since the two glazed facades have an East and West orientation, the solar radiation falling on both facades is expected to be similar during the year. In such a perspective, a variation of the type of aerogel in the windows in the same alternative was not supposed to give interesting results. However, in the case of a North-South orientation of the two glazed facades, such a combination of glazing types would have been an interesting solution, if favouring the use of granular aerogel in the North façade and the use of monolithic aerogel in the South façade.

The thermal losses through the windows timber frames were not considered in this study. The different windows shapes shown in Fig. 1 do not reflect different U-values, which were only calculated for the glass centre. This aspect was not taken in consideration as the windows used in this study are just one of the possible configurations for different glazing ratio. However, the thermal losses through the window frame have a high influence on the final windows U-value, especially for very well insulated glazing solutions, as shown in [37]. This is particularly relevant for windows insulated with monolithic aerogel. Due to the fragility of this material, large glazed areas are difficult to manufacture, and this limits the possible applications of this glazing technology. In addition, by increasing the glazed area, the overall U-value decreases, as the frame is the energy-wise window weak point. In such a perspective, the use of small double-glazed units with monolithic aerogel may give an energy performance equal to the one obtained by using large triple-glazed units with argon.

Summer indoor comfort and energy use for cooling were not considered in this study. When increasing the glazing ratio and using highly insulated windows the indoor temperature may become an issue.

However, by implementing both a natural ventilation strategy (in addition to the existing mechanical ventilation) and a shading strategy is expected to achieve a satisfactory indoor comfort level during the warmest days in Oslo. These technical solutions are not expected to increase the energy use for space heating. Similarly, winter indoor comfort is not considered in this study. By increasing the amount of glazed area, users may experience discomfort due to asymmetric radiation or cold draft given by vertical surfaces at different temperatures (as described in the ISO 7730:2005). However, as the windows type used in the analyses of this study have very low U-values, the surface temperature of their inner glass panes are expected to be very close to the surface temperature of the room walls.

Indoor natural light availability has not been considered in the calculation. The electricity use for lighting is based on the requirement of the Norwegian Standards [28, 29]. Clearly, by varying the glazing ratio and the glazing type the indoor natural light availability is expected to change. However, how higher indoor natural lighting levels can be translated into savings in emissions due to the reduced use of electricity for lighting is a difficult task for residential buildings. As there is not a standard schedule for lighting use in residential buildings, such savings may be only calculated by using scenarios. However, the use of large glazed areas has positive impact on user preferences, as it gives higher access to outdoor view [38-40]. In such a perspective, the impact of using a large fraction of windows with granular aerogel on users' preferences has not been considered in this study. Due to the low visible transmittance and the resulting translucent appearance, double-glazed units with granular aerogel may have a limited application in residential buildings, while the use of monolithic aerogel would give high possibility of application due to the higher visible transmittance.

The energy use required for assembling the different glazing technologies was not considered in this study, due to lack of data for the vacuumed glazing with monolithic aerogel. Detailed information on a full life cycle analysis of different windows can be found in [41]. Similarly, no information was found in literature for the service life of windows with either granular or monolithic aerogel. For this reason, a sensitivity analysis on the service life of such window types has been performed.

The calculation of the lifecycle emissions has only been done by using the average European electricity-to-emissions conversion factor. As discussed in [15], the use of a "green" energy mix (such as the Norwegian energy production) dramatically reduces the amount of emissions credited to the building energy use. In such a perspective, the use of advanced glazing technologies, such as the aerogel glazing, that have higher embodied emissions than those of standard triple-glazed units with argon, would give less significant savings in lifecycle emissions as those presented in this paper. Similarly, the use of other heating systems than heat pumps, such as bio mass boilers or solar collectors, implies the use of different energy-to-emissions conversion factors that influence the building lifecycle emissions.

Finally, the monetary cost of the three different window types was not considered due to the lack of data of windows with monolithic aerogel, which are not a market product.

6. Conclusions

The building energy use and the lifecycle emissions of three different glazing types installed in the energy retrofitting of an apartment building near Oslo were calculated. The glazing types are a triple-glazed unit with argon and U-value of 0.79 W/m K, a double-glazed unit with granular aerogel and U-value of 0.44 W/m K, and a double-glazed unit with monolithic aerogel and U-value of 0.65 W/m K. The window-to-wall ratio was set to 3 different values (0.24, 0.33, and 0.50) to study the effect of large glazing areas on the total lifecycle emissions. The fraction of aerogel glazing area was increased to cover 98% of the total glazed area to estimate the full potential of such a window technology in the building lifecycle emissions abatement. The emissions of the production of aerogel were varied to study the influence of this material in the total building lifecycle emissions. The service life of the aerogel glazing was varied to study the influence of the durability of this technology on the building lifecycle emissions.

The performed energy simulations showed that the substitution of triple-glazing with argon gas with aerogel glazing (either monolithic or granular) saves up to 20% of the delivered energy for space heating, and 6% of the total building delivered energy. The energy use for space heating varied from 16 kWh/m^2 y for an alternative with 0.24 glazing ratio and monolithic aerogel to 20 kWh/m^2 y for an alternative with 0.50 glazing ratio and monolithic aerogel. Similar results were given when the granular aerogel was used. When the fraction of aerogel glazing was increased up to cover at least 96% of the total glazed surface, the energy use for space heating decreased to 10-13 kWh/m^2 y, for the alternative with granular aerogel and 0.24-0.50 glazing ratio. The use of monolithic aerogel gave results for the energy use which were 0.5-1.5 kWh/m^2 y higher. Therefore, the substitution of the argon-insulated windows with the aerogel-insulated windows gave approximately 45% energy savings for space heating and 13% savings for the building energy use (as shown in Table 6).

The calculation of the lifecycle greenhouse gas emissions showed that the embodied emissions of the aerogel glazing do not significantly reduce the achieved savings of building energy use. The difference in lifecycle emissions between the alternatives with argon glazing and aerogel glazing were up to 4% (alternatives with 50% window-to-wall ratio), when a short maintenance schedule was used. This increased to 5% when a long maintenance schedule was used (alternatives with 0.5 window-to-wall ratio). When the fraction of aerogel glazing was increased to cover 98% of the total window area, the achieved savings in lifecycle emissions were 9% (alternatives with 0.5 window-to-wall glazing ratio and short maintenance schedule). In such a perspective, the use of either monolithic or granular aerogel give lower lifecycle emissions than those achieved when only triple-glazed windows with argon were used.

The composition of the embodied emissions of the alternatives with aerogel glazing showed that these windows accounted for up to 43% of the building lifecycle embodied emissions. This revealed a high potential of savings by reducing the embodied emissions of the production of aerogel. However, the analysis performed on the variation of the aerogel embodied emissions gave very small savings in the total lifecycle emissions use (less than 0.5 kg $CO_{2\text{-eq}}/m^2$ y). This was due to the high fraction of lifecycle emissions taken by the building energy use. On the other hand, it was found that the embodied emissions of aerogel had to be increased by at least 8 times to give the same lifecycle emissions of the alternative with windows with argon. Increasing of the windows service life gave higher savings in the lifecycle emissions. These were approximately 1 kg $CO_{2\text{-eq}}/m^2$ y when all the window types had the same service life and the highest window-to-wall ratio.

In conclusion, this study showed that the use of aerogel glazing has a positive effect on the abatement of lifecycle emissions calculated for the energy retrofitting of an apartment building. These savings are however achieved by using an energy mix that credits high emissions to the electricity production. By using a "greener" kWh-to-kg $CO_{2\text{-eq}}$ conversion factor, the influence of the embodied emissions on the final budget of lifecycle emissions given by the use of aerogel glazing is expected to increase. This would therefore reduce the environmental benefits of this glazing technology.

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Table 1. *Thickness, service life, transportation distance, and transportation type of the materials used in the renovated facades. The materials service life is reported for the long and the short maintenance schedule. The building service life is set to 50 years.*

	Thickness (mm)	Long maintenance/replacement schedule (years)	Short maintenance/replacement schedule (years)	Transportation distance (km)	Means of conveyance
External paint	0.1	18	4	175	Van < 3.5 t
Concrete tiling	8.0	40	20	100	Lorry 16-32t
Air gap	28.0	-	-	-	-
Wind barrier	1.0	50	50	150	Van < 3.5 t
Timber framework	250.0	50	50	175	Lorry 16-32t
Insulation (mineral wool)	250.0	50	50	100	Lorry 16-32t
OSB board	18.0	50	50	175	Lorry 16-32t
Existing structure (timber frame with mineral wool insulation)	100.0	-	-	-	-
Gypsum plaster board	13.0	50	50	150	Lorry 16-32t
Internal paint	0.1	16	10	175	Van < 3.5 t
Screws and connectors	-	50	50	175	Lorry 16-32t

Table 2. *Thickness, service life, transportation distance, and transportation type of the materials used in the building (excluding the facades). The materials service life is reported for the long and the short maintenance schedule. The building service life is set to 50 years.*

	Thickness (mm)	Long maintenance/replacement schedule (years)	Short maintenance/replacement schedule (years)	Transportation distance (km)	Means of conveyance
Balconies					
Steel structure	-	50	50	525	Lorry 16-32t
Timber flooring	25.0	30	15	175	Lorry 16-32t
Timber preservative	0.1	3	1	50	Van < 3.5 t
Glazed balusters	3.0	50	50	400	Lorry 16-32t
Paint	0.1	12	8	175	Van < 3.5 t
Roof					
Bitumen	3.0	30	20	150	Lorry 16-32t
Water barrier	1.0	50	50	150	Van < 3.5 t
Insulation (EPS)	400.0	50	50	25	Lorry 16-32t
Plaster	10.0	60	20	150	Lorry 16-32t
Paint	0.1	16	10	175	Van < 3.5 t
Basement					
Cement tiling	8.0	40	20	100	Lorry 16-32t
Plaster	10.0	60	20	150	Lorry 16-32t
Insulation (EPS)	280.0	50	50	25	Lorry 16-32t
Insulation (mineral wool)	100.0	50	50	100	Lorry 16-32t
Bitumen	3.0	30	20	150	Lorry 16-32t
Concrete blocks	80.0	50	50	150	Lorry 16-32t
Cement mortar	10.0	50	20	150	Lorry 16-32t
Gypsum plaster board	10.0	50	50	150	Lorry 16-32t

Table 3. *Glazing ratio of the different retrofitting alternatives. Glazing ratio of the different window types and ratio of aerogel windows/total windows used in the 0.24, 0.33, and 0.50 building glazing ratio.*

		Glazing ratio		
Building glazing ratio		0.24	0.33	0.50
Alternatives "standard" (*g_aer_s* and *m_aer_s*)	Windows with aerogel	0.08	0.12	0.22
	Windows with argon	0.16	0.21	0.28
	Windows with aerogel/total windows	0.33	0.36	0.44
Alternatives "full" (*g_aer_f* and *m_aer_f*)	Windows with aerogel	0.23	0.32	0.49
	Windows with argon	0.01	0.01	0.01
	Windows with aerogel/total windows	0.96	0.97	0.98
Alternatives with argon (*arg*)	Windows with argon	0.24	0.33	0.50
	Windows with aerogel/total windows	0.00	0.00	0.00

Table 4. *Service life, transportation distance, and transportation type of the different window types. The windows service life is reported for the long and the short maintenance schedule. The building service life is set to 50 years.*

	Long maintenance/replacement schedule (years)	Short maintenance/replacement schedule (years)	Transportation distance (km)	Means of conveyance
Triple glazing with argon	60	20	25	Lorry 16-32t
Double glazing with monolithic aerogel	30	10	1525	Lorry 16-32t
Double glazing with granular aerogel	30	10	1525	Lorry 16-32t
Paint	9	4	175	Van < 3.5 t

Table 5. *Description of the layers, centre U-values, and solar heat gain coefficients (SHGC) of the three window types. The different thermal transmittances of aerogel are also reported.*

Window type	Layers					Centre U-value (W/m^2 K)	SHGC	Aerogel thermal transmittance (mW/m K)
Triple glazing with argon	4 mm Lo-E glass	8 mm argon	4 mm Lo-E glass	8 mm argon	4 mm Lo-E glass	0.79	0.46	-
Double glazing with monolithic aerogel	4 mm clear glass	14 mm monolithic aerogel	4 mm clear glass	-	-	0.65	0.74	11.0
Double glazing with granular aerogel	4 mm clear glass	25 mm granular aerogel	4 mm clear glass	-	-	0.44	0.31	13.5

Table 6. *Ratio of the results given by the energy use and building lifecycle emissions (short maintenance) between the alternatives with aerogel-insulated windows and the alternatives with argon-insulated windows with corresponding glazing ratio.*

	Space heating			Building energy use			Building lifecycle emissions (short)		
	24_arg	33_arg	50_arg	24_arg	33_arg	50_arg	24_arg	33_arg	50_arg
24_g_aer_s	0.90	-	-	0.98	-	-	0.99	-	-
24_m_aer_s	0.89	-	-	0.98	-	-	0.98	-	-
33_g_aer_s	-	0.83	-	-	0.96	-	-	0.97	-
33_m_aer_s	-	0.85	-	-	0.96	-	-	0.97	-
50_g_aer_s	-	-	0.78	-	-	0.94	-	-	0.96
50_m_aer_s	-	-	0.79	-	-	0.94	-	-	0.96
24_g_aer_f	0.58	-	-	0.91	-	-	0.94	-	-
24_m_aer_f	0.60	-	-	0.92	-	-	0.94	-	-
33_g_aer_f	-	0.55	-	-	0.90	-	-	0.93	-
33_m_aer_f	-	0.58	-	-	0.90	-	-	0.93	-
50_g_aer_f	-	-	0.51	-	-	0.87	-	-	0.91
50_m_aer_f	-	-	0.57	-	-	0.89	-	-	0.92

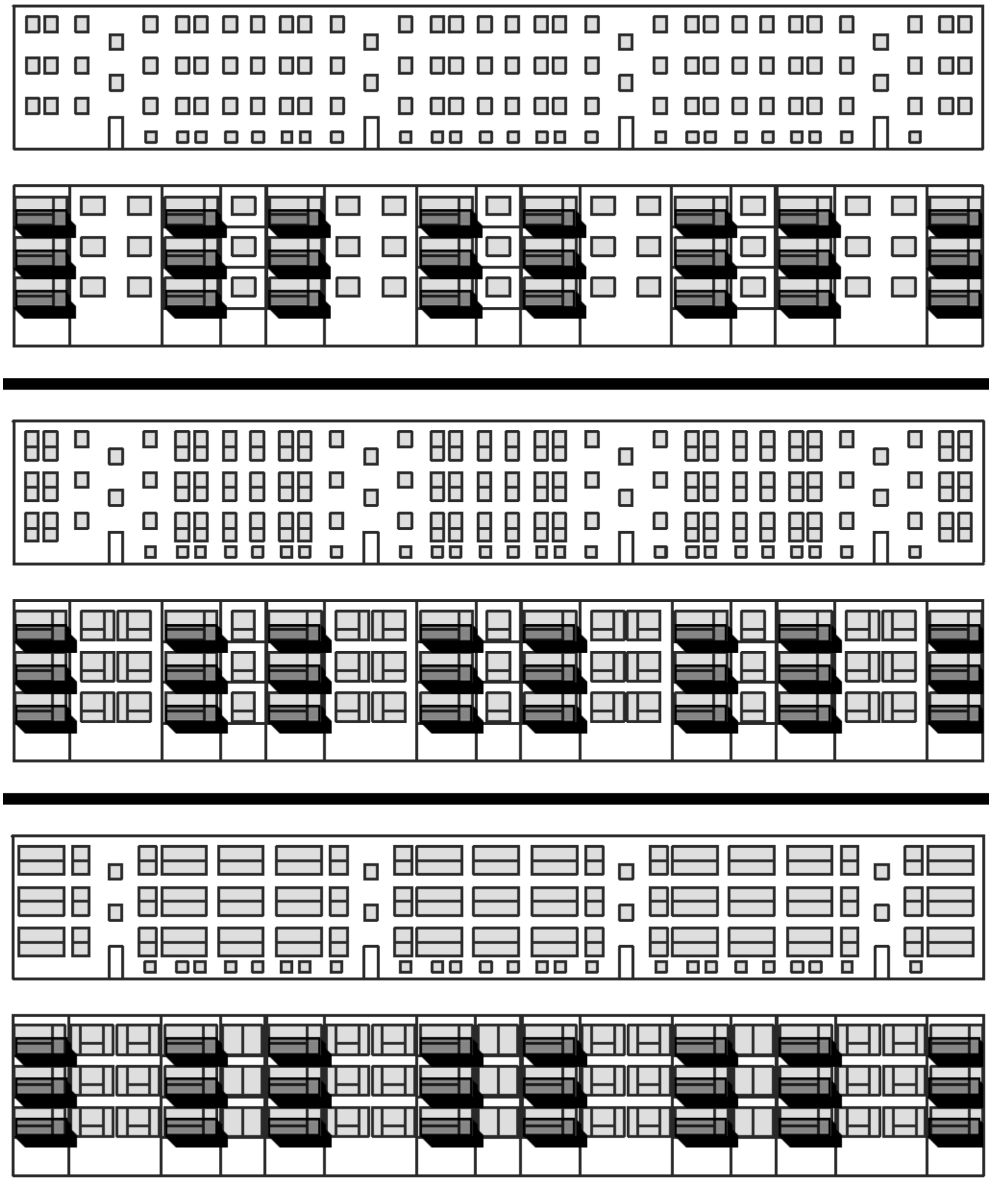

Fig. 1. Drawing of the facades of the different retrofitting alternatives of the Myhrerenga Borettslag. From top, East and West façade of the alternative with 0.24 glazing ratio, 0.33 glazing ratio, and 0.50 glazing ratio.

Figure 2

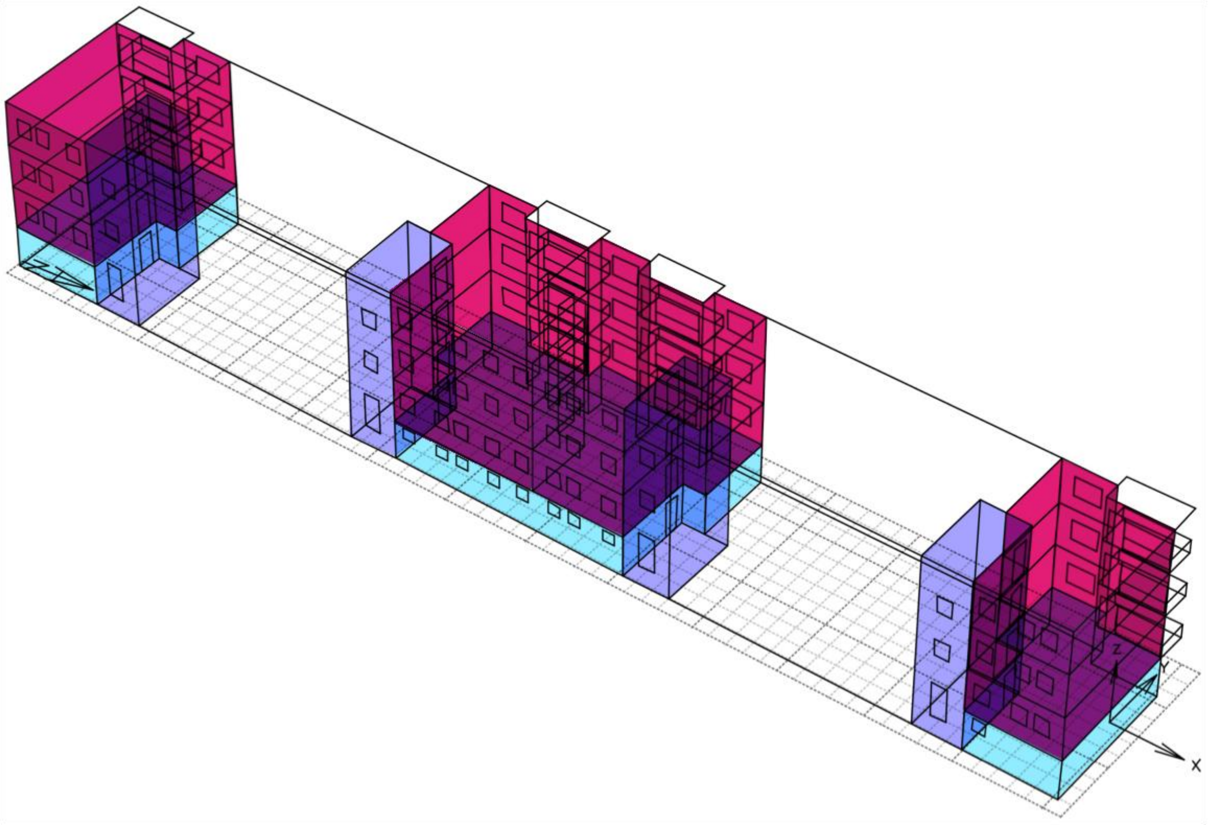

Fig. 2. A CAD drawing of the energy model of the Myhrerenga Borettslag. The apartments are shown in purple. The stairwells and the basements are modelled as unheated spaces and are shown in blue and cyan, respectively. The rest of the building is modelled as two adiabatic zones.

Figure 3

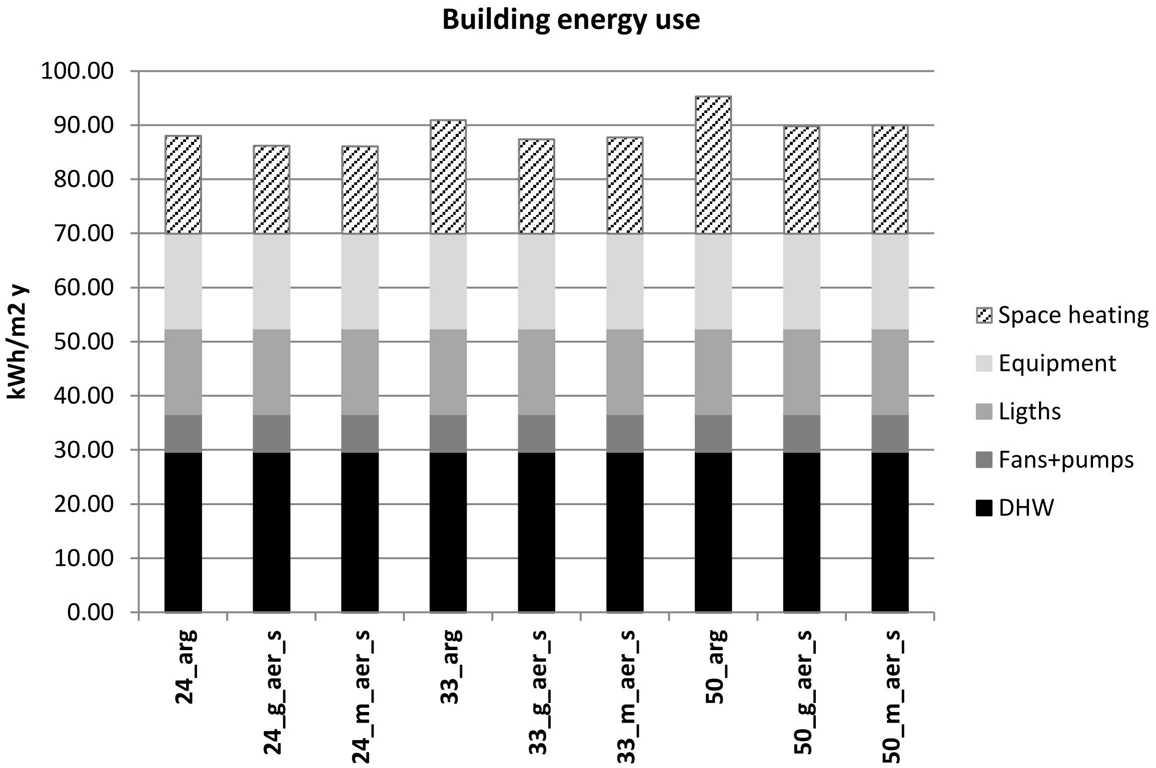

Fig. 3. Annual building delivered energy of the different retrofitting alternatives with "standard" aerogel glazing ratio. Values are normalized to 1 m^2 of heated building area.

Figure 4

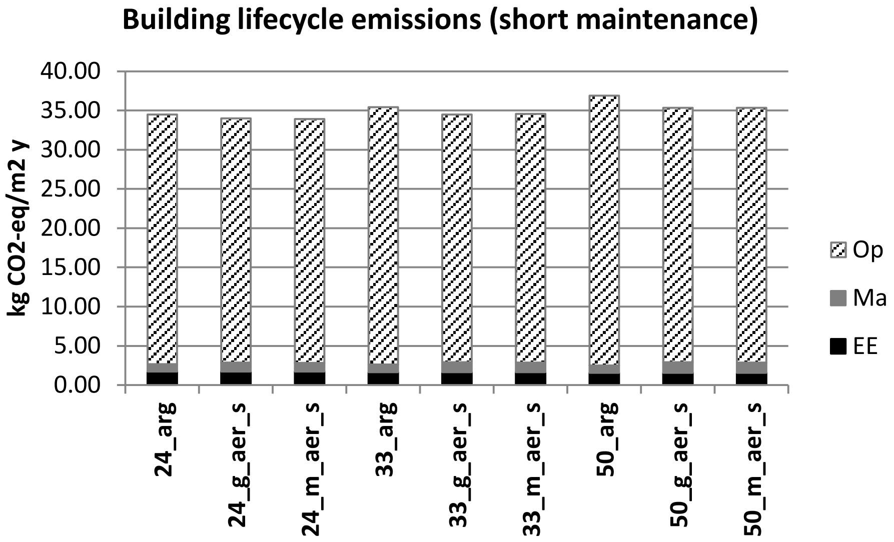

Fig. 4. Annual building lifecycle emissions of the different retrofitting alternatives with "standard" aerogel glazing ratio. Values are given for the phases of material production (EE), maintenance (Ma), and building operation (Op), and are normalized to 1 m^2 of heated building area.

Figure 5

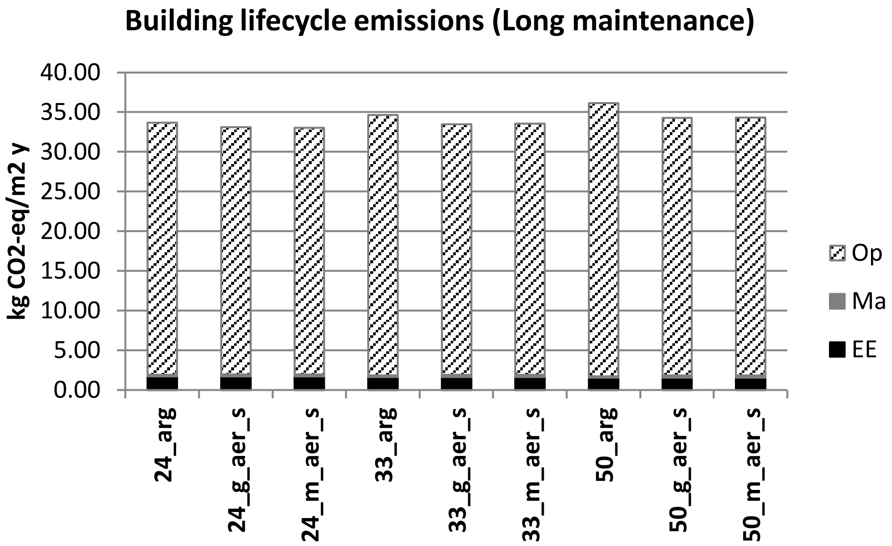

Fig. 5. Annual building lifecycle emissions of the different retrofitting alternatives with "standard" aerogel glazing ratio. Values are given for the phases of material production (EE), maintenance (Ma), and building operation (Op), and are normalized to 1 m^2 of heated building area.

Figure 6

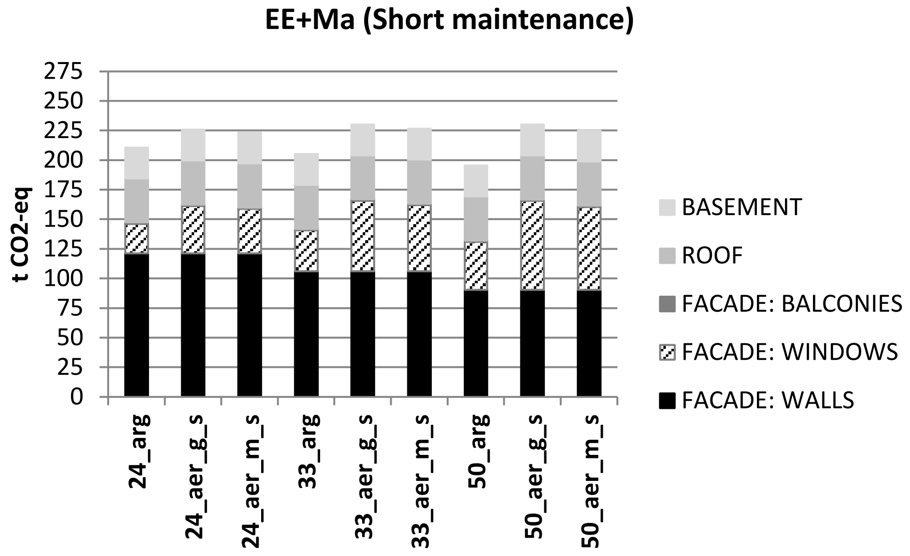

Fig. 6. Lifecycle embodied emissions of the different retrofitting alternatives with "standard" aerogel glazing ratio calculated for the phases of material production (EE), and maintenance (Ma). Values are calculated for the building lifetime and the short maintenance schedule.

Figure 7

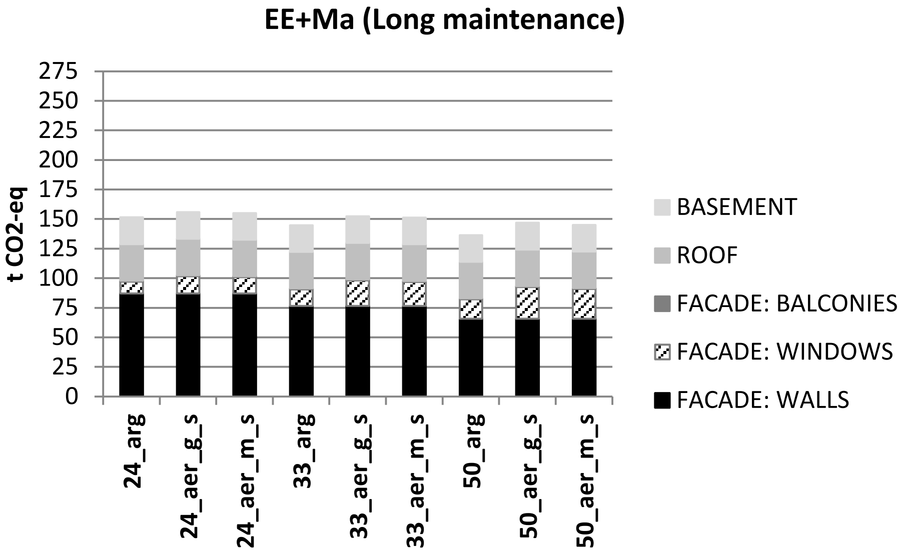

Fig. 7. Lifecycle embodied emissions of the different retrofitting alternatives calculated for the phases of material production (EE), and maintenance (Ma). Values are calculated for the building lifetime and the long maintenance schedule.

Figure 8

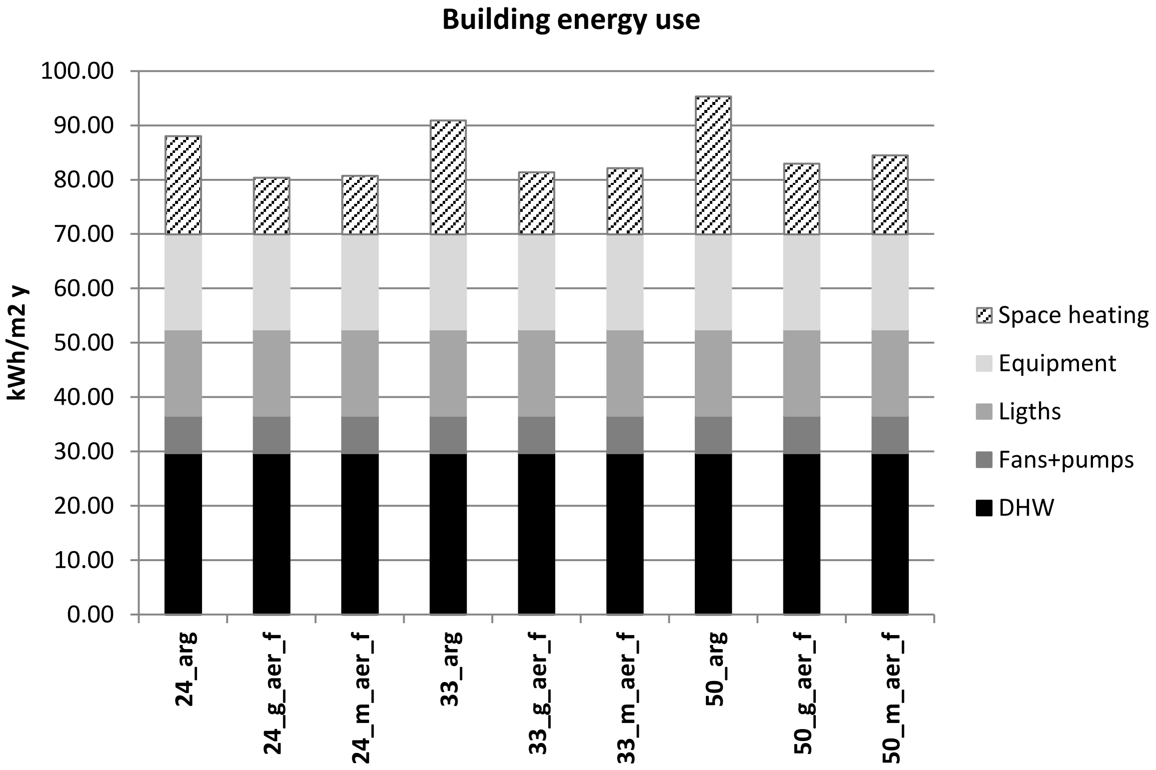

Fig. 8. Annual building delivered energy of the different retrofitting alternatives with "full" aerogel glazing ratio. Values are normalized to 1 m^2 of heated building area.

Figure 9

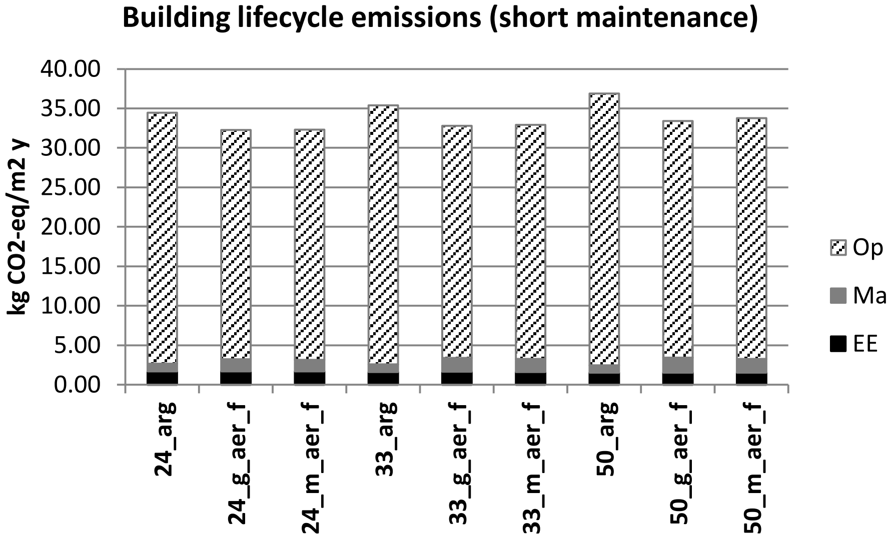

Fig. 9. Annual building lifecycle emissions of the different retrofitting alternatives with "full" aerogel glazing ratio. Values are given for the phases of material production (EE), maintenance (Ma), and building operation (Op), and are normalized to 1 m^2 of heated building area.

Figure 10

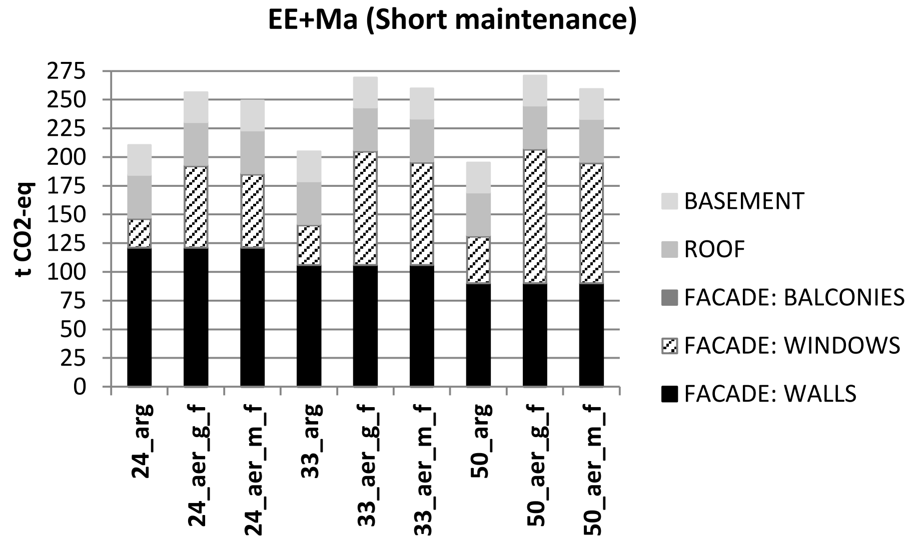

Fig. 10. Lifecycle embodied emissions of the different retrofitting alternatives with "full" aerogel glazing ratio calculated for the phases of material production (EE), and maintenance (Ma). Values are calculated for the building lifetime and the short maintenance schedule.

Figure 11

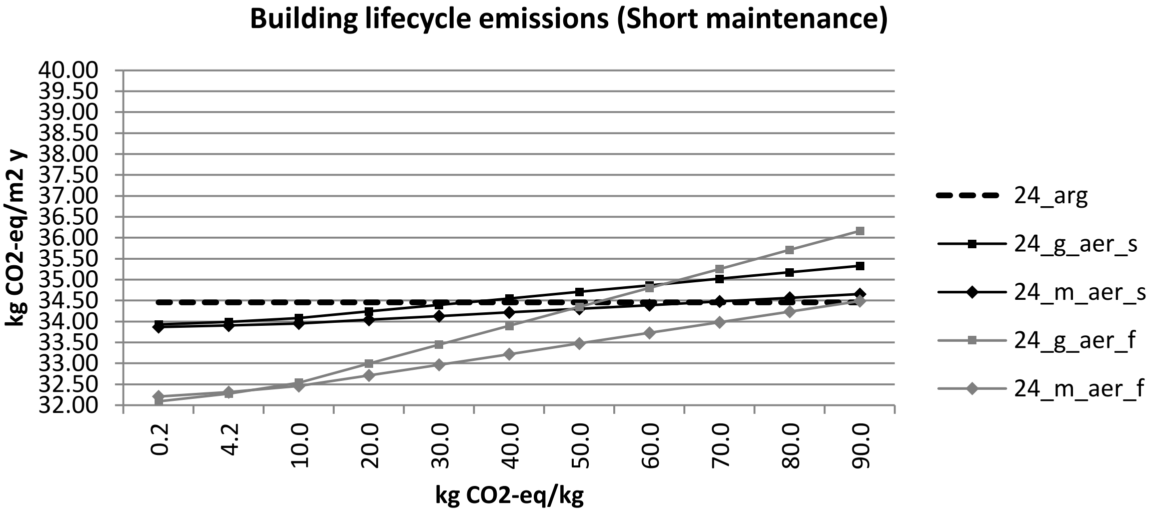

Fig. 11. Annual building lifecycle emissions of the alternatives with 0.24 glazing ratio and different window types. Values are given for different emissions of aerogel production, and are normalized to 1 m^2 of heated building area.

Figure 12

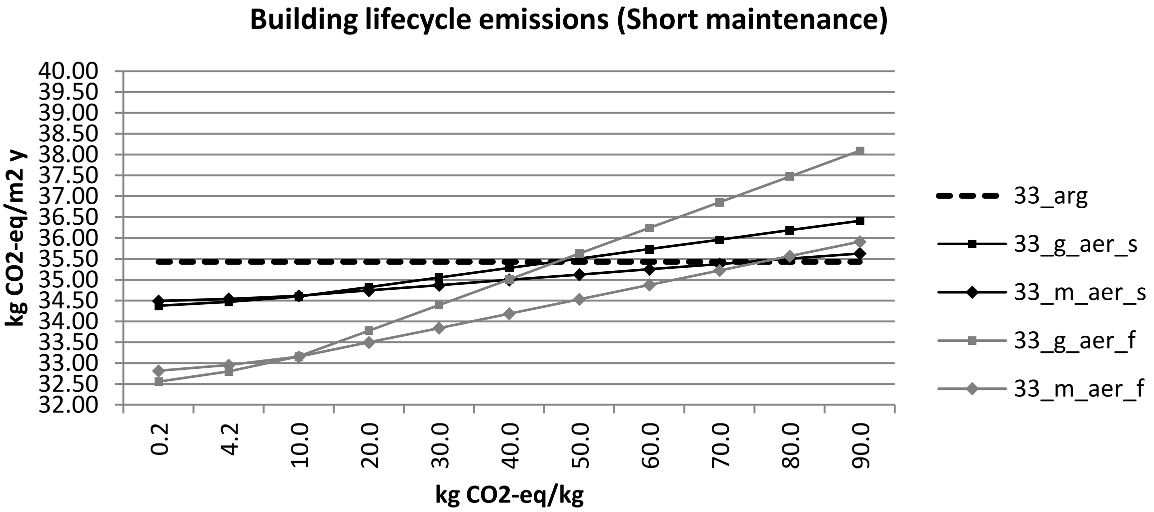

Fig. 12. Annual building lifecycle emissions of the alternatives with 0.33 glazing ratio and different window types. Values are given for different emissions of aerogel production, and are normalized to 1 m^2 of heated building area.

Figure 13

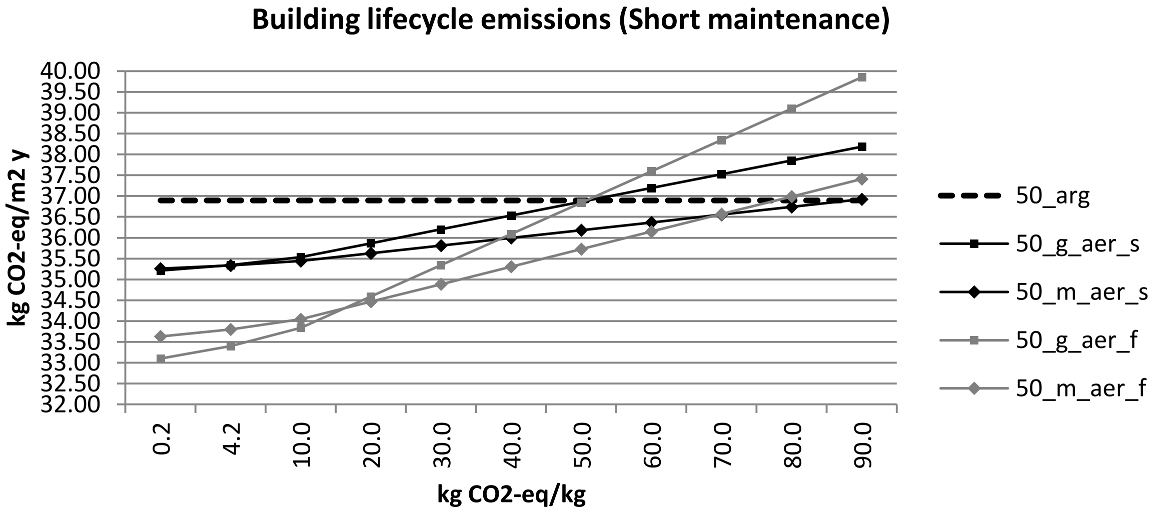

Fig. 13. Annual building lifecycle emissions of the alternatives with 0.50 glazing ratio and different window types. Values are given for different emissions of aerogel production, and are normalized to 1 m^2 of heated building area.

Figure 14

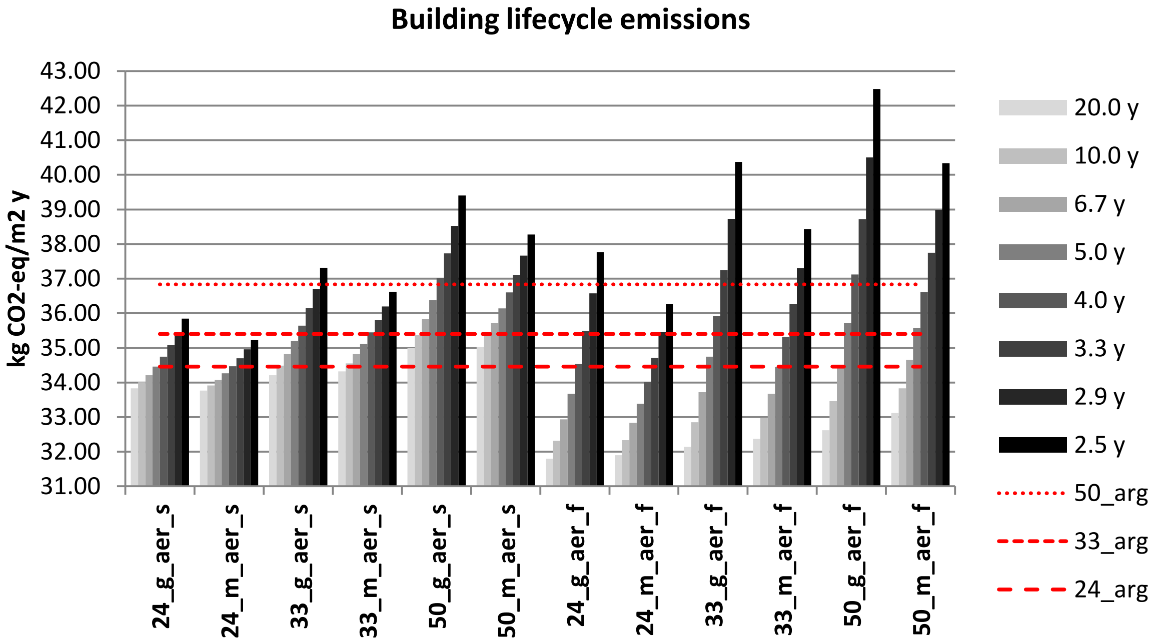

Fig. 14. Annual building lifecycle emissions of the different retrofitting alternatives. Values are given for different service lives of aerogel windows, and are normalized to 1 m^2 of heated building area.