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Consequences of energy retrofitting on the daylight availability in Norwegian apartments

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Abstract

Energy retrofitting solutions applied in residential building envelopes often consist in adding an insulation layer on the building facade and substituting the old windows with better performing ones. Such measures increase the thermal insulation of the envelope and reduce the energy need for space heating, but also reduce the daylight availability, due to the lower visible transmittance of highly insulated windows. This drawback may have strong effect in Norway, where the daylight availability in the winter season is little. This paper investigates into the consequences on energy use for space heating and electricity use for lighting given by the substitution of existing windows with highly insulated windows in Norwegian residential buildings. Three apartment buildings with different construction systems of the external facades and located in Trondheim are investigated. The buildings were built before the 1900, in the first decade of the 1900, and in the 1960s, respectively. The U-value of the external facades varies from 0.96 W/m^{2}K to 0.26 W/m^{2}K, and the U-value of the existing windows varies from 1.6 W/m^{2}K to 2.8 W/m^{2}K. The new windows have a U-value of 0.5 W/m^{2}K. Scenarios are modelled to simulate the use patterns of artificial lighting in the apartments. Use patterns are modelled by considering occupancy hours and type of activity to cover different scenarios. Results show that the substitution of the existing windows reduces the median value of the Daylight Autonomy by at least 50%, and the additional electricity use for lighting is calculated to be between 17% and 64% of the potential energy saving for space heating.

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Keywords: Daylight Autonomy; energy efficiency; windows; electricity use; lighting

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1. Introduction

Daylight and solar radiation have a known influence on human health, by regulating the circadian rhythm, mood and behaviour, and synthesising vitamin D. Disruption of day/night cycles is associated to higher incidence of cardiovascular diseases, psychological problems, depression, and reduction in cognitive functions [1-6]. In such a perspective, windows are the building's most complex physical interface, as they are required to both allow satisfactory daylight penetration, view, and limit the thermal exchange between the indoor space and the outdoor environment. This aspect is critical in high latitudes, such as in Trondheim, were the winter conditions require well insulated buildings and high daylight penetration. The relationship between the thermal insulation, the visible transmittance, and the solar energy transmittance of glazing with either clear or low emissivity glass panes can be described with an asymptotic curve [7-10]. As a consequence, by increasing the glazing thermal insulation, the visible transmittance decreases, which has a negative influence on the availability of daylight in northern climates and the electricity use for lighting [11-13].

1.1. Objective

The scope of this paper is to investigate into the consequences on energy use for space heating and electricity use for lighting given by the substitution of existing windows (centre-glass U-value 1.6 W/m^{2}K and 2.8 W/m^{2}K) with highly insulated windows (centre-glass U-value 0.5 W/m^{2}K) in Norwegian residential buildings. The scope of this work, which focuses on the energy retrofitting of residential buildings, is to evaluate the consequences of installing highly insulated windows on the electricity use for lighting and on the energy use for space heating, in existing residential buildings located in Trondheim, Norway.

2. Methodology

Three apartments are used as case studies in this work, and are described in Table 1. The types of buildings used for the analysis, represent the majority of existing residential constructions in Norway. In order to produce an accurate daylight analysis in the three apartments, the reflectance of the internal surfaces and the furniture is measured using a Minolta LS-100 luminance meter. This is obtained by comparing the luminance values measured on the internal surfaces with those measured on a standard grey card of 18% reflectance. The resulting reflectance is used to characterize the corresponding surface in the 3-D model built for the daylight analysis, performed in Daysim. The illuminance values are calculated on a grid of 0.43 m cell size, placed at 0.80 m from the floor of the apartments. The illuminance results are validated through on-site illuminance measurements, which are not reported in this paper due to space issues. The occupancy schedules and the type of tasks performed by the building users are modelled by proposing three occupancy scenarios and three illuminance tasks, as shown in Table 2. The occupancy time for which the daylight simulations are performed is between 7:30 am and 11:30 pm. The three occupancy schedules (40%, 60%, and 80%) reflect the possible lifestyles of different users. The three lighting tasks (100 lux, 300 lux, and 500 lux) reflect possible activities for which specific illuminance levels are required [14]. Combinations of the above parameters give the scenarios shown in Table 2 for which the Daylight Autonomy (DA) is calculated. The DA is the percentage of the occupied hours of the year when a minimum illuminance level is met by sole daylighting as:

$$DA = \frac{\sum_i (wf_i \cdot t_i)}{\sum_i t_i} \in [0, 1] \quad \text{with} \quad wf_i = \begin{cases} 1 \; if \; E_{daylight} \geq E_{limit} \\ 0 \; if \; E_{daylight} < E_{limit} \end{cases} \tag{1}$$

Where t_i is the occupied time; wf_i is a weighting factor depending on the $E_{daylight}$ and the E_{limit}, which are the horizontal illuminance on the measuring plane given by daylight only, and the limit value of illuminance, respectively [15]. The DA calculation is performed with Daysim [16] Electricity use for lighting is calculated according to three scenarios of types of luminaires: compact fluorescent, LED, and a combination of the two above. The variation of the electricity use for lighting given by the substitution of the windows is calculated in kWh/year for all the scenarios and the three types of luminaires as:

$$Var.el.light. = el.light._{existing\ windows} - el.light._{new\ windows} \tag{2}$$

The calculation of the energy use for space heating is done for the three apartments before and after the substitution of the windows. The characteristics of the new window are shown in Table 1. Electric heaters, with an efficiency of 98% [17] are used for the heating system, which is typical in old apartments in Norway [18]. The operative temperature is 21 C for 16 hours a day and 19 C for 8 hours a day [17]. The annual energy use is calculated by using IDA ICE v.4.7 [19]. The energy savings given by the installation of the new windows are calculated in kWh/year as:

$$En.sav.heat. = en.heat._{existing\ windows} - en.heat._{new\ windows} \tag{3}$$

Table 1. Description of the case buildings.

Case study	Construction year	Description/U-value/Avg. int. surface reflectance	Window type/year/window area to floor area	Window U-value/g-value/Tvis/Orientation	Window frame type/U-value
Building 1	1960s.	36-cm-thick timber frame with 15 cm mineral wool insulation. 0.26 W/m^{2}K. 0.65.	4 mm clear – 12 mm air – 4 mm clear. Mid 1980s. 0.11.	2.8 W/m^{2}K. 0.74. 0.82. Windows on S, E, and W facades.	Wood. 1.50 W/m^{2}K
Building 2	Before 1900.	27-cm-thick wood log construction with 5 cm mineral wool insulation. 0.31 W/m^{2}K. 0.58.	4 mm clear – 12 mm argon – 4 mm low-e. Year 2000. 0.17.	1.6 W/m^{2}K. 0.63. 0.75. Windows on NW facade only.	Wood. 1.50 W/m^{2}K
Building 3	Circa 1900.	46-cm-thick brick construction with 3 cm air gap. 0.96 W/m^{2}K. 0.58.	4 mm clear – 12 mm air – 4 mm clear. Mid 1980s. 0.18.	2.8 W/m^{2}K. 0.74. 0.82. Windows on NW facade only.	Wood. 1.50 W/m^{2}K
All buildings (new windows)	-	-	4 mm low-e – 16 mm argon – 4 mm clear – 16 mm argon – 4 mm low-e.	0.50 W/m^{2}K. 0.35. 0.50.	Wood. 1.50 W/m^{2}K

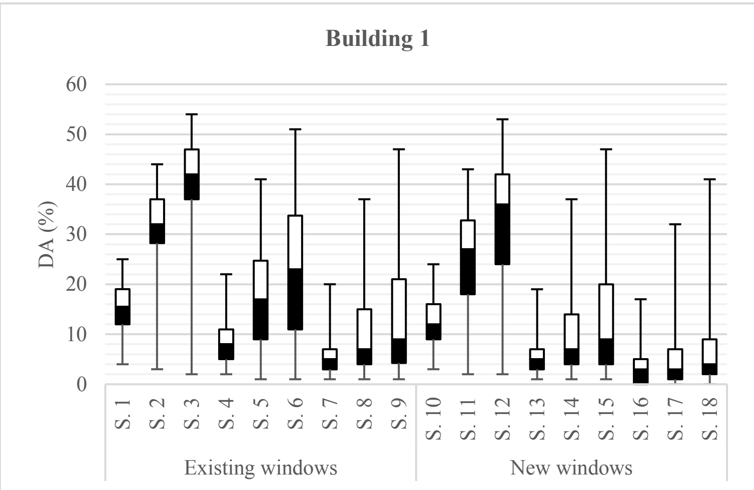
Table 2. Description of the scenarios used in the daylight analysis.

Scenario	Window type	Lux level	Occupancy	Notes
S. 1, S. 2, and S. 3	Existing[(a)]	100	40%, 60%, and 80%	[(a)] Visible transmittance (Tvis) of window is 0.82 for Buildings 1 and 3, and 0.75 for Building 2.
S. 4, S. 5, and S. 6	Existing[(a)]	300	40%, 60%, and 80%	
S. 7, S. 8, and S. 9	Existing[(a)]	500	40%, 60%, and 80%	
S. 10, S. 11, and S. 12	Passive house[(b)]	100	40%, 60%, and 80%	[(b)] Visible transmittance (Tvis) of window is 0.50 for all buildings.
S. 13, S. 14, and S. 15	Passive house[(b)]	300	40%, 60%, and 80%	
S. 16, S. 17, and S. 18	Passive house[(b)]	500	40%, 60%, and 80%	

3. Results

The results of the daylight autonomy, according to Equation (1), are represented as box and whiskers charts, which give the occurrence of the DA on the simulation grid. The median value is given by the demarcation line between the black and the white box. The top and bottom limits of the central box represent the 3rd and the 1st quartile, respectively. The top and bottom limits of the whiskers represent the maximum and minimum values, respectively. The results of the variation of electricity use for lighting, calculated according to Equation (2), are represented as single points. The values given by the circles represent the additional electricity use for lighting given by the substitution of the windows for each of the calculation scenario as in Table 2. The additional electricity use calculated for the scenarios with 300 lux and 60% occupancy is represented with triangles. The visible transmittance of the windows is henceforth abbreviated as Tvis.

Figure 1(a) shows the DA calculated in Building 1. The substitution of the windows gives a substantial reduction in the median value of the DA, especially for the tasks that require higher lux levels and the highest occupancy. As an example the median of the scenario 6 (300 lux, 80% occupancy, Tvis 82%) is 23%, which decreases to 9% in the corresponding scenario with the new windows (Tvis 50%). The median value calculated for the scenarios with 500 lux and 80% occupancy decreases from 9% to 4%, by changing the windows. It can be also noted that the difference between the 1st and the 3rd quartile is reduced when the existing windows are substituted with the new highly insulated ones, as shown in the scenarios 6 and 15, and in the scenarios 9 and 18. The general trend shows that by substituting the existing windows with new windows with a lower visible transmittance, the DA decreases by at least 50% (as shown by the median values). Moreover, the extent of the floor area in which the majority of the illuminance levels (the values falling between 1st and 3rd quartiles) satisfies the tasks required for 300 and 500 lux, decreases too. On the other hand, the results of the DA given for the 100 lux levels show that the spatial availability of the illuminance level that satisfies the 100 lux task is more gradually distributed by using the new windows, as shown by the height of the boxes representing the scores falling between the 1st and the 3rd quartile.



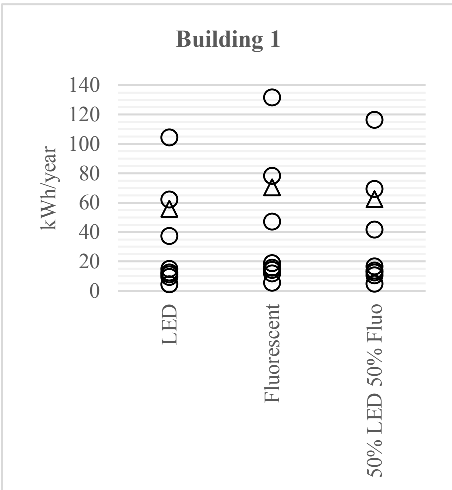


Fig. 1 (a) results of DA; (b) additional electricity use for lighting (scenario with 300 lx and 60% occ. is represented with a triangle).

Figure 1(b) shows the variation of energy use for both the electricity use for lighting, according to Equation (2), and the space heating given by the installation of the new windows in Building 1, according to Equation (3). The results show that the maximum additional electricity use is at least 104 kWh/year is LEDs are used, and 132 kWh/year if compact fluorescent lamps are used. These values are to be subtracted from the energy saving given by the more thermally insulated windows, which accounts for 365 kWh/year. This means that more than 30% of the expected saving is cut off by the additional electricity use, which is translated directly in a 30% cut-off of the expected saving in the electricity bill, as the heating system is electric-based.

Figure 2(a) shows the DA calculated in Building 2. Similarly to the results shown in Figure 1(a), the installation of the new highly-insulated windows reduces the median value of the DA. In Building 2, median of the scenario 6 (300 lux, 80% occ., Tvis 75%) is 2.6 times higher than that of the scenario 15 (300 lux, 80% occ., Tvis 50%). Moreover, the values of DA comprised between the median and the 3rd quartile (with box) span on a larger extension than that of those comprised between the 1st quartile and the median.

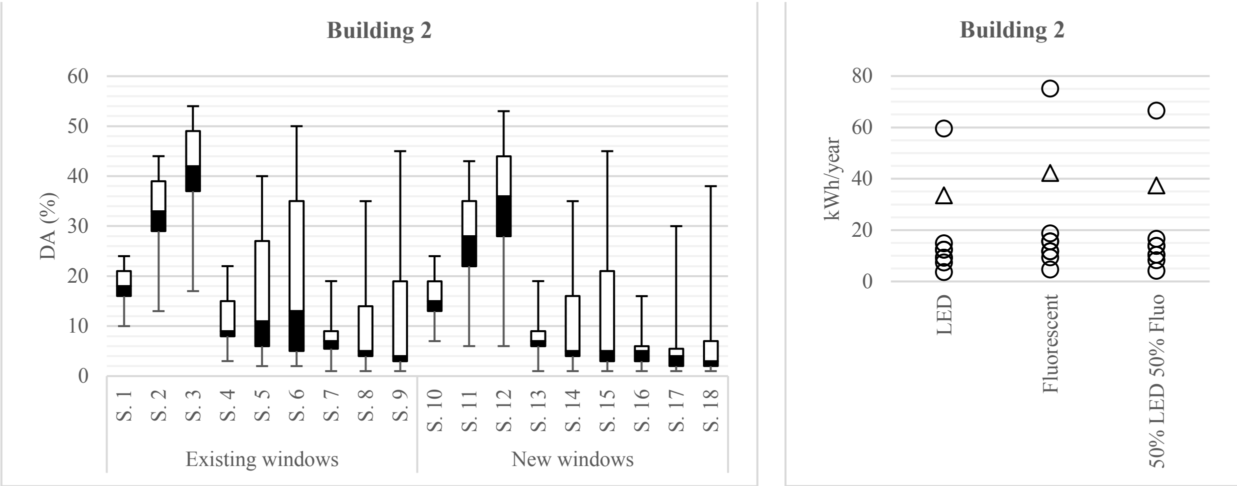


Fig. 2 (a) results of DA; (b) additional electricity use for lighting (scenario with 300 lx and 60% occ. is represented with a triangle).

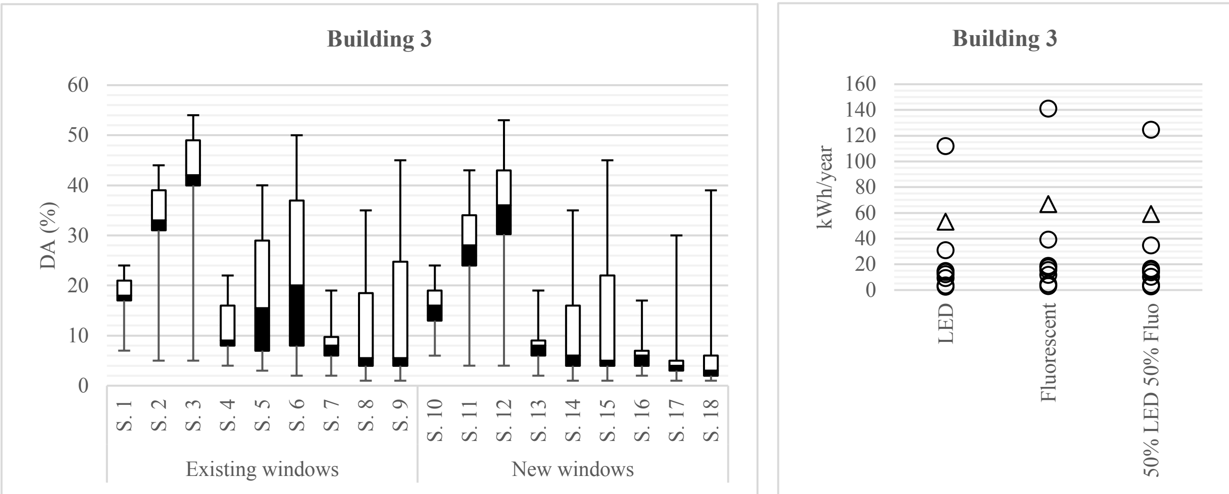


Fig. 3 (a) results of DA; (b) additional electricity use for lighting (scenario with 300 lx and 60% occ. is represented with a triangle).

As shown in Figure 2(b), the additional electricity use for daylighting is up to 75 kWh/year for the compact fluorescent lamps. Given that the energy saving for space heating is calculated as 117 kWh/year, the total energy saving can be as little as 42 kWh/year. In such a perspective, the use of compact fluorescent and a scenario with 300 lux task requirement and 80% occupancy can lead to a reduction of potential energy savings of 64%.

Figure 3(a) shows the results of the DA calculated in Building 3. The most notable difference between this chart and those in Figures 1(a) and 2(a) is shown by the largest difference between the values for the 3rd quartile and the 1st quartile in scenarios 6 and 9. The calculated energy saving for space heating are 850 kWh/year, which is at least six times the additional electricity use given by the new windows installed, as shown in Figure 3(b).

4. Conclusions

Three residential buildings located in Trondheim, Norway, are used for estimating the influence of substituting existing windows with highly-insulated windows on the energy use for space heating and the electricity use for lighting. The results shows that in the three cases, the energy saving for space heating largely compensates the additional electricity use for lighting. In Building 1 and 3, where the existing windows have a U-value of 2.8 W/m^{2}K, the cut of the energy saving for space heating given by the additional electricity use for lighting is 36% and 17%, respectively. This cut increases to 64% in Building 2, due to a U-value of 1.6 W/m^{2}K of the existing windows, thus diminishing the benefit of installing highly-insulated windows. The ratio between the fenestration area and the floor area is the most critical factor in determining how much energy for space heating is saved in contrast to how much electricity use for lighting is needed, in the buildings investigated. Building 3 (window/floor ratio of 0.18) shows higher energy savings for space heating in comparison to electricity use for lighting than Building 1 (window/floor ratio of 0.11). This aspects looks to overcome the difference of orientation between Building 1 (W, S, and E) and Building 2 (NW only), and the internal surface reflectance (0.65 in Building 1 and 0.58 in Building 3). The additional electricity use for lighting largely depend on the performed task and the occupancy. It was found that in all buildings the worst-case scenario is represented by performing a task requiring 300 lux for 80% occupancy.

Further energy savings for space heating are possible by installing an additional insulation layer in the walls, which, by consequence, mitigates the negative effect of the loss of daylight. It must be noted that the resulting increased wall thickness reduces the daylight penetration, especially in winter conditions in northern climates. This aspect was not covered in this paper and it worth being investigated in future works. In conclusion, the installation of highly insulated windows has a considerable effect on limiting the potential energy saving for space heating in residential buildings in Norway, and largely depends on the daylight autonomy calculated for the performed task and occupancy time.

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