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The cost efficiency of improved roof windows in two well-lit nearly zero-energy houses in Copenhagen

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Abstract

Roof windows are efficient and flexible daylight sources that are essential in certain types of houses if they are to achieve sufficient daylighting throughout. Previous studies have indicated that, for such buildings to meet nearly zero-energy targets in an easy and robust way without compromising on daylighting and thermal comfort, the thermal properties of roof window glazing, frames and junctions need to be considerably improved. However, the barriers to improving roof windows to levels above the current best standard practice remain great so long as we do not know the economic benefits of such improvements. The aim of this study was to quantify the scope for investing in improved roof window solutions in buildings insulated to consume nearly zero-energy. Based on two single-family houses in Copenhagen with typical roof windows and adequate daylighting, the study identified the prices at which various types of roof window improvements would have to be made available to achieve the same cost efficiency as improved insulation. If the improvements can be made available for less than these prices, the installation of improved roof windows would make it cheaper to construct well-lit and comfortable nearly zero-energy homes.

Keywords: Roof windows, Cost-effectiveness, Window design, Glazing, Frame, Solar-control coating, Space heating, Climate-based daylighting, Adaptive thermal comfort

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Highlights

- The scope for investing in improved roof windows was investigated.
- Improvements beyond current best standard practice were studied.
- Improvements preserving daylighting and thermal comfort in the houses were studied.
- The savings in insulation costs by improving the roof windows were identified.
- Improvements in roof window frame and junctions showed the largest potential.

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1. Introduction

With the recast of the Energy Performance of Buildings Directive adopted in 2010 [1], all new buildings in the European Union are required to consume nearly zero-energy by the end of 2020. This creates a strong need for research in technologies and solutions that can not only provide sufficient daylighting and thermal comfort in homes but also meet the ambitious energy requirements in a cost-efficient way.

Previous studies on the energy performance of windows in well-insulated residential buildings [25] have indicated that the degree to which solar gains can be utilised decreases with space-heating demand. Furthermore, studies on the impact of various window parameters on energy, daylighting and thermal comfort in rooms insulated to nearly zero-energy levels [6,7] have shown that the thermal properties of windows are becoming increasingly important if nearly zero-energy targets are to be met in a reasonably robust and flexible way without compromising on sufficient daylighting and thermal comfort. This is especially true of roof windows in northern European climates. An earlier study by the present authors [7] on individual rooms in a 1½-storey single-family house with a simplified floor plan identified the need for considerably better thermal properties in glazing, frames, and junctions than are current best standard practice. Roof windows are efficient and flexible daylight sources that are essential in certain types of houses if they are to achieve sufficient daylighting throughout. However, the large convection heat losses due to their slope and the problems in reducing heat loss through junctions between roof and window mean that roof windows still have a lot more scope for improvement than façade windows.

While more and more insulation is being inserted in the building envelope to comply with the increasing requirements for space heating, a lack of knowledge is still preventing roof windows with considerably improved thermal properties from being made commonly available and installed. Doubt about the economic benefits and scope for investing in such improvements may be one of the barriers. With the large insulation thicknesses needed in the building envelope to consume nearly zero energy, however, the costs of compensating for building components that are not optimised for the new conditions by means of insulation have increased significantly. It is therefore likely that we are about to reach a situation in which a new generation of considerably improved roof windows need to be made available to ensure a reasonably cost-optimal choice of basic building components.

1.1. Aim of study

The hypothesis behind this study was that roof windows with considerably improved thermal properties compared to what is currently best standard practice would make the construction of nearly zero-energy homes with sufficient daylighting and thermal comfort more cost-efficient. However, any attempt to determine the cost efficiency of various improvements directly by means of common economic evaluation techniques [8,9] would require qualified cost estimations for roof window products that do not yet exist or are not yet commonly produced. The use of such techniques would therefore

be of limited purpose in this case. Instead this study took a different approach, where the aim was to quantify the scope for investing in improved roof windows. In the Danish Building Code [10,11], a fixed requirement for the maximum energy use permitted in nearly zero-energy residential buildings has already been defined, and from 2020 all new houses will have to comply with this requirement in one way or another. This made it possible to establish a measure of the scope for investing in improved roof window by holding the energy saving potential of various types of roof window improvements up against the cost of saving the required energy by current means. Given that a building has the best high-end practice façade windows currently available and that all other building components affecting the space-heating demand have been optimised to nearly ideal levels, the amount of insulation inserted in the building envelope is the parameter that would most likely be used to compensate for the performance of the roof windows. For two new single-family houses in Denmark with typical use of roof windows, we therefore investigated how much less insulation building owners would need in the houses to comply with Danish Building Regulations if they installed various types of improved roof windows instead of the options that are currently the best standard practice. The cost of this amount of insulation not needed can then be seen as a measure of the scope for investing in improved roof windows.

It will be up to the manufacturers to determine the prices at which the various types of improved roof windows can be made available. However, if the improvements (including the replacements needed within a time frame corresponding to the lifetime of insulation) can be made available at prices that are less than the savings in insulation costs identified throughout this paper, near future energy requirements could be met in a cheaper and more cost-effective way than by using so much insulation.

1.2. Literature review

For façade windows, Jaber and Ajib [12] and Karabay and Arıcı [13] have examined the cost-optimal selection of glazing using common economic evaluation techniques requiring cost estimation inputs. As part of a study by Hansen and Vanhoutteghem [14] on the economic optimisation of new low-energy homes, the cost-effectiveness of existing windows has also been evaluated in relation to other building components. For roof windows, however, very few studies could be found that consider their performance in very well-insulated homes. Studies by Foldbjerg and Asmussen [15], Du et al. [16] and Du [17] have investigated the effect of existing roof windows on energy, daylighting and thermal comfort in well-insulated residential buildings, but none of these studies examined the economic effect of improving roof windows to levels beyond the currently best standard practice. By doing so, the present study contributes to new knowledge within the field.

2. Methodology

The study considered two large single-family houses, in which approximately one third of the floor area depends on roof windows for sufficient daylighting:

- Case A – a 1½-storey house with 45° sloped roof windows on the 1st floor.
- Case B – a one-storey quadratic house with horizontal roof windows in the core area.

Figs. 1 and 2 show the floor plans, key dimensions, and room types in each thermal zone for the two houses. In both houses, we assumed air-tight building envelopes with construction details of high quality and the best available heat recovery efficiency for ventilation, etc. (see Table 1). It should be noted that Case A is a considerably more compact type of house than Case B (see the transmission areas in Table 1), while both houses are considerably more compact than the long and narrow one-storey single-family houses with only façade windows commonly found in Denmark.

The overall methodology of the study is sketched in Fig. 3. As indicated in the figure, a reference scenario with the best high-end practice façade windows currently available and the best standard-practice roof windows currently available was first established for the two houses (see REF in Tables 2 and 3). This scenario was set up for sufficient daylighting and thermal comfort based on knowledge from previous studies on roof and façade windows at room level [6,7], following the procedure described in Section 2.2, and daylighting was tested through simulation. Furthermore, to make it possible to see how the findings depend on the space-heating demand of the reference, each house was insulated to comply with three different targets for space-heating demand, where the best corresponds to Danish

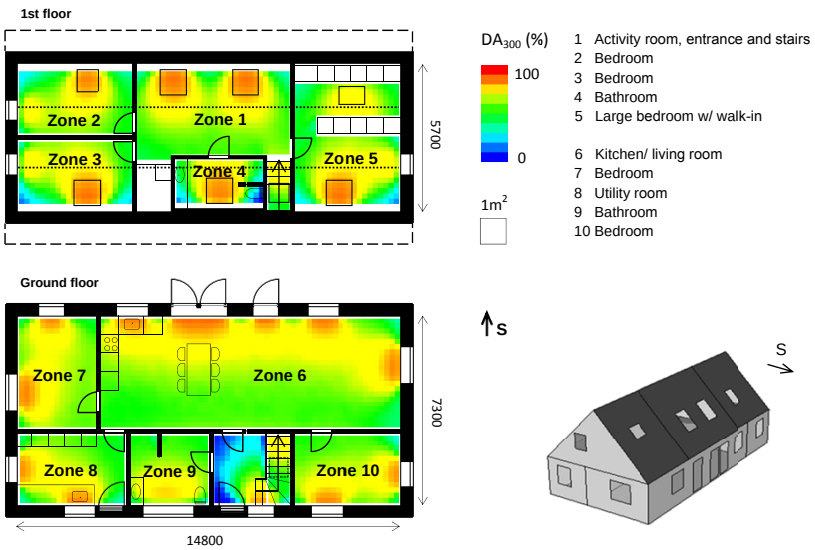


Figure 1: Plan drawing for Case A with daylight distribution for the reference scenario, shown as the percentage of daylight hours with illuminances of at least 300 lx in the sensor points.

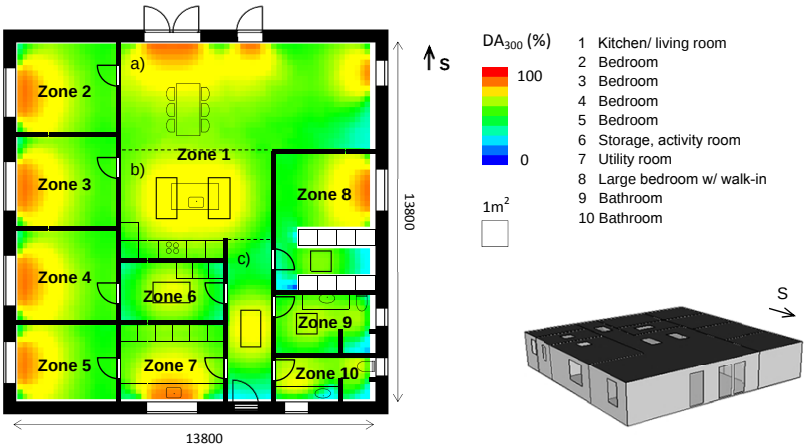


Figure 2: Plan drawing for Case B with daylight distribution for the reference scenario, shown as the percentage of daylight hours with illuminances of at least 300 lx in the sensor points.

requirements for nearly zero-energy consumption (see Section 2.1.1). This was done following the procedure described in Section 2.3. Then, the thermal comfort for the reference scenario was checked (see Section 2.4), before the effect of replacing the standard-practice roof windows in the reference scenario with various types of roof window improvements was investigated. The façade windows were kept the same. These investigations consisted of the following two parts (see Fig. 3):

1. A part showing the effect of changes to the individual glazing parameters, one at a time. The parameter variations in this part were carried out based on two scenarios similar to the reference scenario, but where the solar energy transmittance (g-value) of all roof window glazing corresponded to either no solar control (g-value as high as possible) or nearly ideal solar control (g-value as low as possible without reducing the light transmittance of the glazing). From this part, it should be possible to estimate the energy saving potential of an arbitrary improvement consisting of small changes in the parameters combined or changes in one single parameter alone. Furthermore, the scope for investing in improvements with small energy saving potentials can be estimated by multiplying these saving potentials by the cost of saving 1 kWh/m^2 by means of insulation for the reference scenario (see Section 2.6.1).

2. A part showing the effect of a number of specific examples of improved roof windows #A-E (see Tables 2 and 3 and Section 2.5). For these options, the scope for investment was determined directly based on the cost of the insulation no longer needed to achieve an acceptable space-heating demand after installing the improved windows (see Section 2.6.2).

Where any change to the roof windows affected the light transmittance (LT) of the glazing, the glazing size was adjusted to maintain sufficient daylighting.

Finally, the effect of increasing window sizes to more than needed for sufficient daylighting and the robustness of the scope for investment to changes in the reference scenario were briefly addressed.

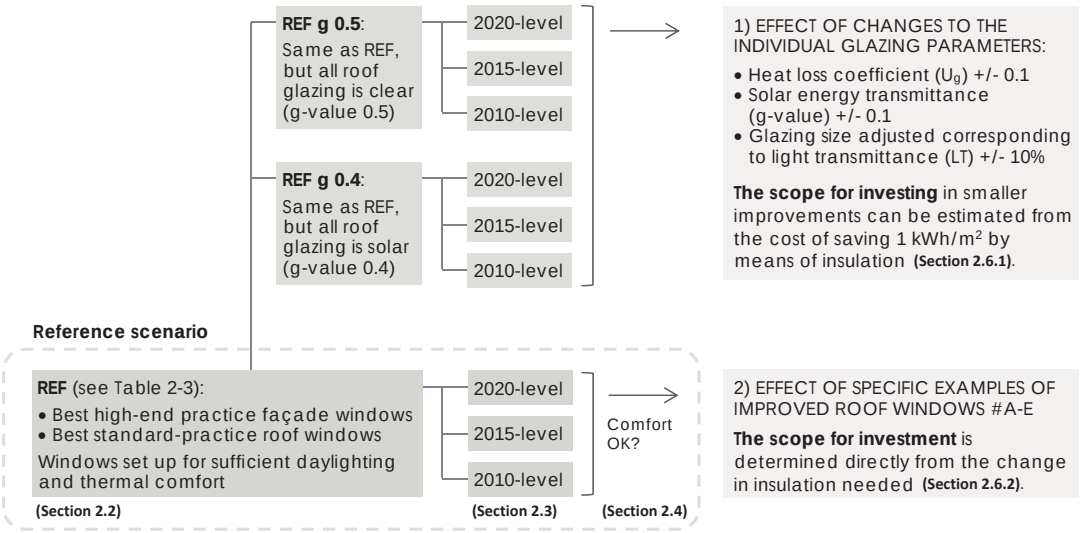


Figure 3: Overview of the methodology. The left-hand side shows the scenarios used as a basis for carrying out the two investigations on the roof windows, which are shown on the right-hand side. The 'reference scenario' is the basis for the second investigation, while two variations of the reference scenario are the basis for the first investigation. All scenarios were insulated to comply with three different energy requirements, before carrying out the investigations.

Space-heating demand and operative temperatures were simulated using EnergyPlus [18] in combination with the tool jEPlus [19,20] for automated parametric analysis, while daylighting for the reference scenario was tested using the RADIANCE-based daylighting analysis tool DAYSIM [21]. Matlab was used for post-processing of simulation outputs, and further modelling assumptions can be found in Section 2.7. Section 2.1 specifies the performance parameters and criteria used.

Table 1: Thermal key parameters and system specifications for the two houses.

	Case A	Case B
Building size		
Gross floor area (m^2), wall thicknesses of 0.4 m	213	213
Internal floor area (m^2)	190	190
Transmission area (inner dimensions) 1)		
Walls (m^2), before subtracting windows	137 (151)	138 (187)
Roof (m^2), before subtracting windows	153 (179)	190 (213)
Ground floor (m^2)	108 (126)	190 (213)
Total transmission area per internal floor area (-)	2.1	2.7
Cold bridge lengths (inner dimensions)		
Foundation (m), psi = 0.15 W/m K	44	55
Other junctions (m), psi = 0.05 W/m K	75	65
System properties and internal loads 2)		
Heating set point (°C)	20	20
Venting set point (°C)	23	23
Infiltration rate (h^{-1})	0.05	0.05
Maximum venting rate (h^{-1})	3 (+ 6 and 9)	3 (+ 6 and 9)
Mechanical ventilation rate (h^{-1})	0.6	0.6
Efficiency of heat recovery (-)	0.9	0.9
Internal loads, including lighting (W/m^2)	5	5

1) The surface areas used for calculation of insulation costs are shown in brackets. These assume construction thicknesses of 0.4 m for walls and 0.7 m for roofs irrespective of insulation level.

2) Internal loads and ventilation rates were inserted based on the internal floor area of the zones and air change rates assume a room height of 2.5 m in all zones.

2.1. Performance parameters and evaluation criteria

In Danish homes, mechanical cooling is normally not installed and electricity consumption for lighting is not part of the requirement for acceptable energy use. So for residential buildings in Denmark, the main variable defining the energy usage is the space-heating demand (Section 2.1.1), while daylighting and thermal comfort are evaluated based on separate criteria (Sections 2.1.2 and 2.1.3).

2.1.1. Targeted space-heating demands

According to the nearly zero-energy requirements for residential buildings that will apply in Denmark from 2020 [11], the annual primary energy usage for covering space heating, domestic hot water, and electricity for pumps and ventilation is defined as no more than 20 kWh/m^2, where the primary energy factors are 0.6 for district heating and 1.8 for electricity. For the two houses considered, this leaves a final energy usage for space heating of no more than approximately 12 kWh per m^2 gross floor area per year. Two less ambitious space-heating targets (see Table 4 and Fig. 4) were similarly established based on Danish energy requirements for residential buildings from 2010 and 2015.

Table 2: Properties of glazing, frame and junctions for the reference roof and façade windows (REF) and for the five examples of roof window improvements (#A-E) investigated – Case A.

			Glazing properties				Properties of frame and junctions					Total heat loss coefficients [3]		Total window area [4]
			U_g 45° (W/m^2 K)	U_g 90° (W/m^2 K)	g-value [1] (-)	LT (%)	Width (m)	U_f (W/m^2 K)	Psi $_g$ (W/m K)	Psi $_w$ (W/m K)	Specific heat loss [2] (W/K)	U_w' (W/m^2 K)	U_g' (W/m^2 K)	A_{win} (m^2)
Façade	REF	Best high-end practice		0.50	0.39* (0.50)	70	0.09	0.8	0.035	0.01	0.583	0.70	0.92	32.3
Roof	REF	Best standard practice	0.73	0.71	0.39* (0.50)	70	0.09	1.5	0.050	0.10	1.460	1.35	1.87	13.2
	#A	Higher g-value	0.73	0.71	0.50 (0.50)	70	0.09	1.5	0.050	0.10	1.460	1.35	1.87	6.5 [5]
	#B	Improved frame and junctions	0.73	0.71	0.39* (0.50)	70	0.11	0.7	0.025	0.05	0.768	0.93	1.35	14.1
	#C	Improved glazing, 2-pane added	0.46	0.41	0.30* (0.40)	55	0.09	1.5	0.050	0.10	1.460	1.15	1.50	16.0
	#D	Improved glazing, frame and junctions (#B+#C)	0.46	0.41	0.30* (0.40)	55	0.11	0.7	0.025	0.05	0.768	0.75	1.02	16.9
	#E	2-pane glazing with higher g-value	1.40	1.10	0.43* (0.60)	78	0.09	1.5	0.050	0.10	1.460	1.85	2.62	11.9

1) Values representing close to ideal solar-control coating (marked with '*') assume that the g-value equals 55% of the light transmittance (LT). Values used for north-oriented glazing with no need for solar control are shown in brackets.

2) Specific heat loss of frame and junctions (including the connection between roof/walls and window) for a window with standard outer dimensions of 1.23 by 1.48 m.

3) U_w' includes all heat loss from glazing, frame and junctions, as projected onto the window area, and refers to the window with standard dimensions above.

U_g' includes all heat loss from glazing, frame and junctions, as projected onto the glazed area, and refers to the area-weighted average of the actual window dimensions inserted in the houses. Both coefficients are given for the effective slope.

4) Total window area inserted in the building.

5) Only south-oriented roof windows were improved.

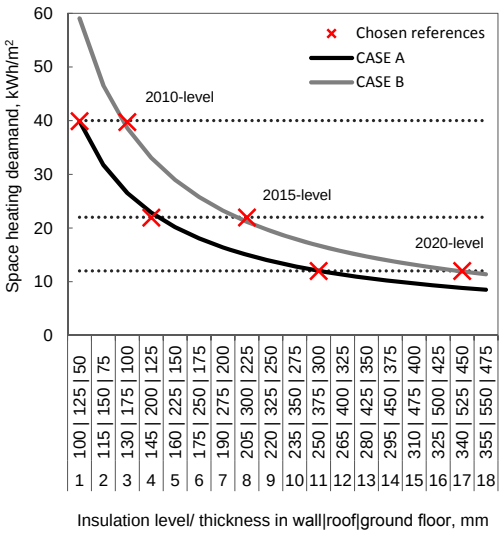


Figure 4: Space-heating demand as a function of insulation level for the reference scenario, showing the insulation levels needed in the houses to comply with the three energy requirements.

Table 3: Properties of glazing, frame and junctions for the reference roof and façade windows (REF) and for the five examples of roof window improvements (#A-E) investigated – Case B.

			Glazing properties				Properties of frame and junctions					Total heat loss coefficients [3]		Total window area [4]
			U_g 00° (W/m² K)	U_g 90° (W/m² K)	g-value [1] (-)	LT (%)	Width (m)	U_f (W/m² K)	Psi $_g$ (W/m K)	Psi $_w$ (W/m K)	Specific heat loss [2] (W/K)	U_w' (W/m² K)	U_g' (W/m² K)	A_{win} (m²)
Façade	REF	Best high-end practice		0.50	0.39* (0.50)	70	0.09	0.8	0.035	0.01	0.583	0.70	0.86	31.7
Roof	REF	Best standard practice	1.25	0.90	0.39*	70	0.09	2.3	0.030	0.10	1.730	1.89	2.77	8.5
	#A	Higher g-value	1.25	0.90	0.55	70	0.09	2.3	0.030	0.10	1.730	1.89	2.77	8.5
	#B	Improved frame and junctions	1.25	0.90	0.39*	70	0.11	0.7	0.025	0.05	0.768	1.29	1.94	9.1
	#C	Improved glazing, 3-pane added	0.50	0.38	0.28*	50	0.09	2.3	0.030	0.10	1.730	1.33	1.81	10.8
	#D	Overall improvement, 3-pane added in the light well	0.50	0.38	0.28*	50	0.09				0.375	0.58	0.79	10.8
	#E	Same as #D, but the added pane is diffuse	0.50	0.38	0.28*	50 diff	0.09				0.375	0.58	0.80	10.1

1) Values representing close to ideal solar-control coating (marked with '*') assume that the g-value equals 55% of the light transmittance (LT). Values used for north-oriented glazing with no need for solar control are shown in brackets.

2) Specific heat loss of frame and junctions (including the connection between roof/walls and window) for a window with standard outer dimensions of 1.23 by 1.48 m.

3) U_w' includes all heat loss from glazing, frame and junctions, as projected onto the window area, and refers to the window with standard dimensions above.

U_g' includes all heat loss from glazing, frame and junctions, as projected onto the glazed area, and refers to the area-weighted average of the actual window dimensions inserted in the houses. Both coefficients are given for the effective slope.

4) Total window area inserted in the building.

2.1.2. Evaluation of thermal comfort

The Adaptive Thermal Comfort (ATC) model in EN 15251 [22] was used to evaluate thermal comfort. Given that occupants are free to use windows for venting, adjust their clothing, and adapt to indoor conditions in other ways, this model states that the comfortable operative temperature is a function of the running mean outdoor air temperature at the location. The upper limit for thermal comfort is therefore not a fixed temperature, but a variable temperature that depends on recent temperatures outdoors. For this study, too much discomfort (or 'overheating') was deemed to have occurred when operative temperatures (T_o) in a zone exceeded the upper comfort limit provided by Class II of this model (referred to as 'Adaptive Limit') for more than 100 h per year. This corresponds well with the recently updated comfort criterion for homes in the Danish Building Code of maximum 100 h above 27°C [11,23]. Throughout this paper, the number of hours with operative temperatures exceeding 26°C will also be provided for information, since this was the parameter previously used in Denmark for evaluation of thermal comfort in residential buildings [24].

2.1.3. Evaluation of daylighting

Danish legislation only vaguely defines sufficient daylighting in buildings. For this study, windows were dimensioned based on two criteria for sufficient daylighting, corresponding to those used in previous studies on roof and façade windows at room level [6,7]. With 'space' referring to measuring positions evenly distributed over a horizontal plane 0.85 m above floor level, these are:

1. Illuminance levels of at least 300 lx in 75% of the space for 50% of the daylight hours (Spatial coverage of DA 50% $\geq$ 75%).
2. Daylight factors of at least 2.1% in 50% of the space (Median DF $\geq$ 2.1%).

The first criterion is based on recommendations for Spatial Daylight Autonomies in offices established by IES [25]. This criterion is fully climate-based and the main basis used for designing all spaces in the houses for comparable daylighting. The second criterion refers to an approach presented by Mardaljevic and Christoffersen [26,27] that relates daylight factors to the diffuse daylight access at a specific location. For a position in the room that meets the daylight factor suggested above for the Danish climate, diffuse daylight levels of at least 300 lx should be received in that position for 50% of the daylight hours. This criterion was used together with the fully climate-based criterion to ensure that daylighting in the rooms receiving the most direct sun will meet some minimum standards under overcast conditions. Throughout this paper, the percentage of daylight hours with illuminances exceeding 300 lx in 50% of the space (Median DA), which should preferably be around 60%, will also be provided for information. It was assumed that occupants can use internal screens or curtains to avoid glare if needed.

Table 4: Maximum space-heating demand for the houses according to Danish Building Regulations for 2010, 2015 and 2020 (nearly zero-energy), and the U-values needed to meet these targets for the reference scenario.

	Case A			Case B		
	2010	2015	2020	2010	2015	2020
Maximum space-heating demand (kWh/m^2)	40.0	22.0	12.0	40.0	22.0	12.0
Space-heating demand of reference (kWh/m^2)	39.9	21.9	12.0	39.7	21.9	12.0
U-value wall (W/m^2 K)	0.31	0.22	0.14	0.25	0.17	0.10
U-value roof (W/m^2 K)	0.31	0.18	0.10	0.22	0.13	0.07
U-value ground floor (W/m^2 K)	0.30	0.18	0.10	0.22	0.13	0.07
Energy saved per cm increased insulation thickness [1)] (kWh/m^2 cm)	3.5547	1.1468	0.3463	2.5439	0.8417	0.2522

1) Extracted from EnergyPlus simulations of the houses with 25 mm more insulation in all constructions.

2.2. Set-up of the windows for daylighting and thermal comfort

In addition to venting through opening of windows, appropriate window design is essential for achieving sufficient daylighting in a space without overheating. Previous studies on the impact of roof and façade windows on energy, daylighting and thermal comfort in nearly zero-energy homes [6,7] have shown that sufficient daylighting can be achieved in solar-exposed rooms without overheating by using well-dimensioned windows with close to ideal solar-control coating (g-value as close to half of the light transmittance of the glazing as possible). This was true as long as the rooms had a reasonable layout for daylighting, meaning that it was generally possible to position the windows for good daylight distribution. For example, façade windows should be used only to serve areas closer to the façade than approximately 4-5 m [6], otherwise the overly large glazing areas needed to provide the innermost parts with daylighting would lead to overheating. For rooms with such a reasonable layout for daylighting, the studies showed that, whatever the choice of light transmittance (LT) for the glazing, the use of solar-control coating left some flexibility between the minimum glazing size for daylighting and the maximum glazing size for thermal comfort.

These findings (summarised in Table 5) give reason to believe that houses with any floor plan can be set up for sufficient daylight and thermal comfort, based on information about the glazing area needed for daylighting in just a few typical rooms, by following this approach:

1. Divide each thermal zone into spaces that can reasonably be served by windows with a certain slope and orientation (referred to as 'daylit spaces').

2. For each daylit space, use the information about daylighting in typical rooms to select the glazing area needed with the given LT, and use common-sense design rules for daylighting to position a number of windows in the space having this glazing area in total.

3. Use close to ideal solar-control coating on south/east/west-oriented and horizontal glazing, and leave the g-values for north-oriented glazing as high as possible to maximise solar gains.

In the present study, this approach was used to set up the two houses for sufficient daylighting and thermal comfort. For the reference scenario, the glazing area needed in each daylit space was first estimated using the glazing-to-floor ratios for minimum daylighting in Table 5. Then daylighting was tested through annual simulations of the hourly illuminance distributions in DAYSIM. Where needed, the size and position of the windows were adjusted using one to two iterations.

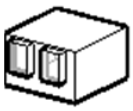
For the scenarios with other light transmittances of the roof window glazing than in the reference scenario (70%), glazing sizes were adjusted in accordance with the change in LT using a scaling factor extracted from Table 5.

2.2.1. Example of window dimensioning for the reference scenario

Tables 6 and 7 show rather detailed information about how the reference scenario was set up for daylighting: the division of the houses into daylit spaces, the glazing area and dimensions inserted in each space, and the final daylight achievements in each thermal zone. The final daylight distributions are also shown in the plan drawings for the two houses in Figs. 1 and 2.

To exemplify the approach, Fig. 2 sketches the division of the kitchen/living room in Case B (Zone 1) into three different daylit spaces, (a)-(c). The front part (a) at a maximum distance of 4.2 m from the façade was side-lit by south- and west-oriented façade windows, while the central kitchen-part (b) was top-lit by two roof windows positioned to give as even a distribution of daylight as possible. Finally, the corridor (c) was given one central roof window. The latter is not an optimal choice for daylight distribution, but a compromise with practical considerations, since too many small windows would lead

Table 5: Glazing-to-floor ratios (%) needed in previously studied rooms[1)] [6,7] with reasonable layout for daylighting, to achieve daylighting of 300 lx in 75% of the space for 50% of the daylight hours (Spatial coverage of DA 50% $\geq$ 75%). The ratios needed for a daylight factor of 2.1% in half of the space (Median DF $\geq$ 2.1%) are shown in brackets. The table also indicates the need for solar-control coating to avoid overheating.

Orientation	South		Horizontal		North
Slope	90°	45°	00°	45°	90°
					
LT 70%	15.6 (17.8)	9.7 (8.5)	10.0 (6.6)	13.2 (8.5)	21.3 (17.8)
LT 60%	17.4 (20.2)	11.0 (9.6)	11.5 (7.5)	15.1 (9.6)	24.5 (20.2)
LT 50%	20.7 (23.7)	12.7 (11.2)	13.2 (8.7)	17.9 (11.2)	29.5 (23.7)
LT 40%	25.0 (30.1)	15.0 (13.6)	16.0 (10.5)	21.4 (13.6)	36.4 (30.1)
LT 30%	34.1 (43.0)	19.2 (17.6)	20.8 (13.2)	27.9 (17.6)	- (43.0)
LT 20%		27.8 (25.4)	31.4 (19.0)	40.2 (25.4)	
LT 10%		45.2 (42.0)	54.5 (38.6)		
Solar-control coating [2)]	Close to ideal	Close to ideal	Close to ideal	Not needed	Not needed

1) These rooms assumed a glazing head-height of 2.4 m for façade windows and thicknesses of 0.45 m for both roof and walls.
2) Close to ideal solar-control coating means that the g-value equals nearly half of the light transmittance (LT).

to greater heat losses through frame and junctions and more absorption of light in the light well than fewer windows of a reasonable size.

South-, east- and west-oriented façade glazing was dimensioned based on the glazing-to-floor ratios of 17.8% suggested in Table 5 for the diffuse criterion (Median DF $\geq$ 2.1%), while all other glazing was dimensioned based on the climate-based criterion (Spatial coverage of DA 50% $\geq$ 75%).

Since differences between the zone floor area (used for determining ventilation rates and internal heat loads) and the area used for evaluation of daylighting may affect the chances of finding a window design that provides sufficient daylighting without overheating, Tables 6 and 7 also include a parameter indicating the daylit fraction of each zone.

Table 6: Set-up of the reference scenario for daylighting for Case A, showing the division of the house into daylit spaces, the glazing inserted for each space and the resulting daylight achievement in each thermal zone. The light transmittance of all glazing is 70%, and the area-weighted average glazing-to-floor ratio finally inserted in the various types of spaces is shown in brackets underneath the slope and orientation. Performance indices that do not meet the targets are marked with '*'.

Zone with daylit spaces	Zone floor area	Floor area of daylit space	Inserted glazing-to-floor ratios				Inserted glazing		Daylit fraction of zone	Daylight performance indices		
			S/E/W-90°	N-90°	S-45°	N-45°	Area	Dimension [1], nR/F: w x h		Spatial coverage of DA 50% (%)	Median DA (%)	Median DF (%)
	(m^2)	(m^2)	(20%)	(22%)	(14%)	(19%)	(m^2)	(m)	(-)	(target: ≥ 75)	(≥ 60)	(≥ 2.1)
1 *Activity etc. S/N*	*33.9*									*74 * [2]*	*60*	*2.3*
- Main part		20.0			14.0%		2.80	2R: 1.0 x 1.4	0.83			
- Stairs		4.4				18.1%	0.80	1R: 0.8 x 1.0	1			
- Entrance		5.4		22.2%			1.20	1F: 1.0 x 1.2	1			
2 *Bedroom S/E*	*12.8*									*75*	*63*	*2.2*
- Façade part		4.2	19.0%				0.80	1F: 0.8 x 1.0	0.93			
- Inner part		7.7			12.4%		0.96	1R: 0.8 x 1.2	0.93			
3 *Bedroom N/E*	*12.8*									*75*	*66*	*3.2*
- Façade part		4.2	19.0%				0.80	1F: 0.8 x 1.0	0.93			
- Inner part		7.7				18.1%	1.40	1R: 1.0 x 1.4	0.93			
4 *Bathroom N*	*7.6*	6.8				20.5%	1.40	1R: 1.0 x 1.4	0.90	*67 **	*67*	*4.3*
5 *Large bedroom S/N/W*	*23.9*									*75*	*63*	*3.0*
- Façade part		4.2	19.0%				0.80	1F: 0.8 x 1.0	0.93			
- Inner part		7.5				18.5%	1.40	1R: 1.0 x 1.4	0.93			
- Walk-in		6.4			15.7%		1.00	1R: 1.0 x 1.0	0.56			
6 *Kitchen/ living S/W*	*52.1*	52.1	20.3%				10.56	3F: 1.0 x 2.0, 1F: 1.4 x 1.2, 2F: 1.2 x 1.2	1	*96*	*63*	*1.9 **
7 *Bedroom S/E*	*13.8*	13.8	20.9%				2.88	1F: 1.4 x 1.2, 1F: 1.0 x 1.2	1	*95*	*66*	*2.2*
8 *Utility room N/E*	*12.1*									*83*	*63*	*2.4*
- Back part		6.4		22.5%			1.44	1F: 1.2 x 1.2	1			
- Gable part		5.7	21.1%				1.20	1F: 1.0 x 1.2	1			
9 *Bathroom N*	*9.3*	9.3		21.6%			2.00	1F: 2.0 x 1.0	1	*90*	*60*	*2.5*
10 *Bedroom N/W*	*12.0*									*94*	*65*	*2.5*
- Back part		6.3		23.0%			1.44	1F: 1.2 x 1.2	1			
- Gable part		5.7	21.1%				1.20	1F: 1.0 x 1.2	1			

1) Glazing head-height for façade windows was 2.1 m.

2) Daylight achievements for this zone were affected by the difficult daylight conditions in the entrance. For most of the zone, the spatial coverage was 87%.

2.2.2. Evaluation of daylight achievements and final glazing ratios for the reference scenario

The performance indices in Tables 6 and 7 and the daylight distributions in Figs. 1 and 2 generally show well-lit houses where the daylight criteria are met in most zones, while some spaces had more difficult conditions for daylighting than others. The north-oriented bathroom in Case A (Zone 4), for example, was generally well-lit, but too large for the light to be properly distributed with only one window. The same was the case for the storage/activity room in Case B (Zone 6). It should also be noted that the kitchen/living room on the ground floor in Case A (Zone 6) received 300 lx for 50% of the time in almost the entire space. Under overcast conditions, however, this room was slightly too deep to receive sufficient daylighting at the back.

Comparison of the glazing-to-floor ratios finally inserted (Tables 6 and 7) with the ratios suggested for glazing with LT 70% in Table 5 shows that these are very similar for both roof and façade windows in Case B. In this house, the ratios inserted were on average less than 1% greater than the ratios suggested. For the sloped roof windows in Case A, however, the glazing-to-floor ratios inserted were approximately 4-6% more than the ratios suggested. This may partly be due to the difficulties in achieving a coverage of 75% in some of the loft rooms with one-sided sloped ceilings, where the difficult layout for daylighting was typically compensated for by increasing the glazing size of the roof windows

Table 7: Set-up of the reference scenario for daylighting for Case B, showing the division of the house into daylit spaces, the glazing inserted for each space and the resulting daylight achievement in each thermal zone. The light transmittance of all glazing is 70%, and the area-weighted average glazing-to-floor ratio finally inserted in the various types of spaces is shown in brackets underneath the slope and orientation. Performance indices that do not meet the targets are marked with '*'.

	Zone with daylit spaces	Zone floor area	Floor area of daylit space	Inserted glazing-to-floor ratios			Inserted glazing		Daylit fraction of zone	Daylight performance indices		
				S/E/W-90°	N-90°	00°	Area	Dimension [1], nR/F: w x h		Spatial coverage of DA 50% (%)	Median DA (%)	Median DF (%)
		(m^2)	(m^2)	(19%)	(22%)	(11%)	(m^2)	(m)	(-)	(target: ≥ 75)	(≥ 60)	(≥ 2.1)
1	*Kitchen/ living S/W*	*76.5*								*87*	*62*	*2.5*
	- Façade part (a)		41.6	17.8%			7.40	3F: 1.0 x 2.0, 1F: 1.0 x 1.4	1			
	- Inner part (b)		24.1			10.6%	2.56	2R: 0.8 x 1.6	1			
	- Corridor (c)		10.8			10.4%	1.12	1R: 0.8 x 1.4	1			
2	*Bedroom (S)/E*	*14.0*	14.0	18.9%			2.66	1F: 1.9 x 1.4	1	*97*	*62*	*2.3*
3	*Bedroom E*	*14.0*	14.0	18.9%			2.66	1F: 1.9 x 1.4	1	*97*	*62*	*2.3*
4	*Bedroom E*	*14.0*	14.0	18.9%			2.66	1F: 1.9 x 1.4	1	*97*	*63*	*2.4*
5	*Bedroom (N)/E*	*11.7*	11.7	19.1%			2.24	1F: 1.6 x 1.4	1	*94*	*62*	*2.2*
6	*Storage/ activity (-)* [2]	*10.1*	10.1			11.1%	1.12	1R: 0.8 x 1.4	1	*64 **	*55 **	*3.3*
7	*Utility room N*	*12.6*	12.6		21.1%		2.66	1F: 1.9 x 1.4	1	*94*	*62*	*2.7*
8	*Large bedroom W*	*21.1*								*70 **	*57 **	*2.1*
	- Main part		11.7	19.1%			2.24	1F: 1.6 x 1.4	1			
	- Walk-in		5.9			10.9%	0.64	1R: 0.8 x 0.8	0.63			
9	*Bathroom W*	*9.4*								*72 **	*56 **	*2.7*
	- Façade part		3.5	20.0%			0.70	1F: 0.7 x 1.0	1			
	- Inner part		5.9			10.9%	0.64	1R: 0.8 x 0.8	1			
10	*Bathroom N/W*	*7.0*								*74 **	*61*	*2.5*
	- West part		3.5	20.0%			0.70	1F: 0.7 x 1.0	1			
	- North part		3.5		25.6%		0.90	1F: 0.9 x 1.0	1			

1) Glazing head-height for façade windows was 2.3 m.

2) No façade, only roof windows.

rather than the façade windows. Furthermore, the ratios inserted for south/east/west-oriented façade windows in Case A were on average about 2% greater than the ratios suggested, which may be partly due to the lower head-height for façade windows in this house.

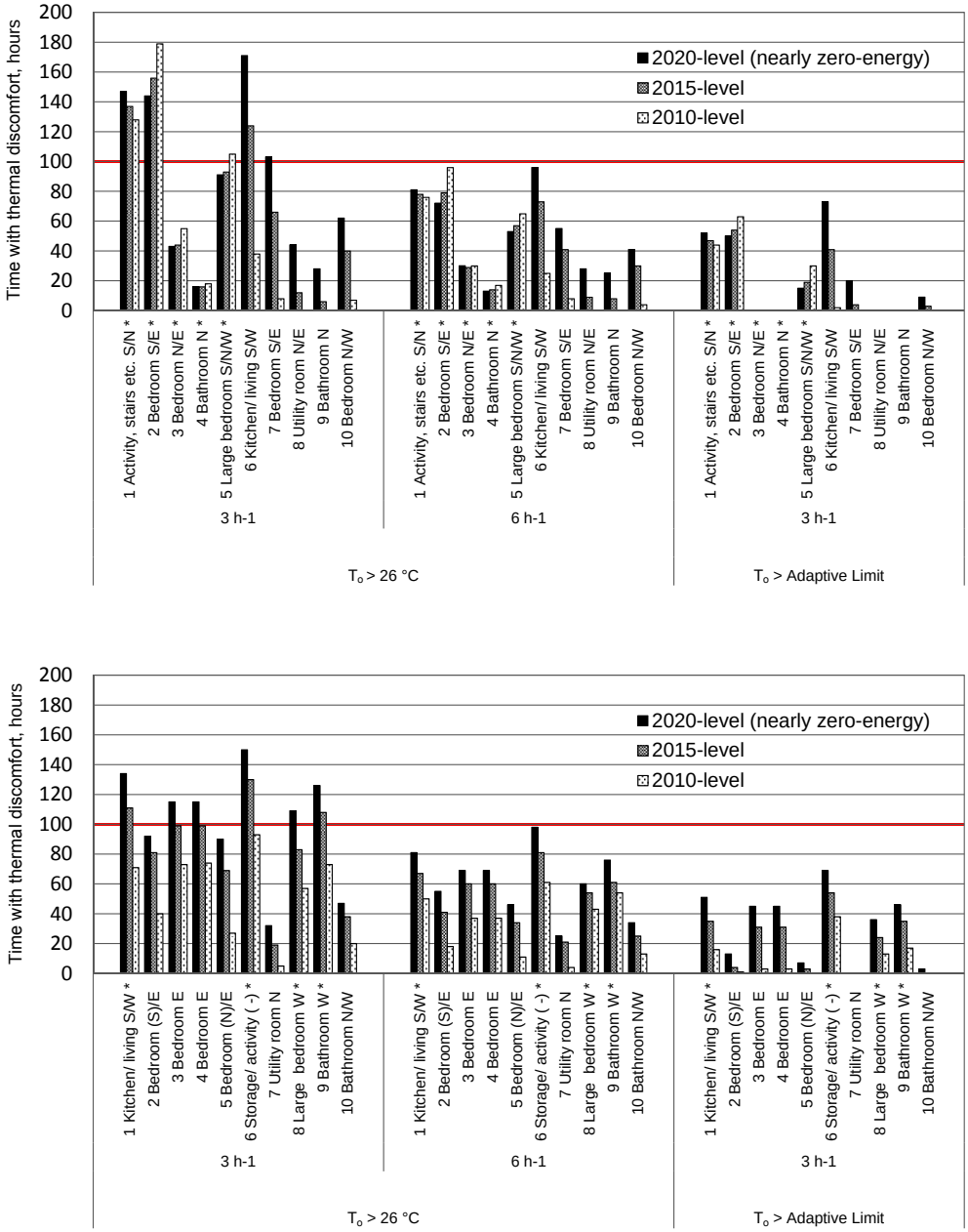


Figure 5: Time with operative temperatures (T_o) in the various zones exceeding 26°C and the adaptive thermal comfort limit for the reference scenario. The results are shown for Case A (top) and Case B (bottom) for the three different insulation levels and the maximum air change rates for venting of 3 h^{-1} and 6 h^{-1}. Zones with roof windows are marked with '*'.

2.3. Insulation for the three different space-heating targets

Fig. 4 shows for the reference scenario how the insulation thicknesses needed for walls, roof and ground floor to meet the three space-heating targets (see Section 2.1.1) were extracted from simulations of the two houses with various insulation levels, using linear interpolation between the nearest steps. Insulation material with a heat conductivity of 0.037 W/m K was assumed. Table 4 shows the resulting insulation thicknesses and U-values for the reference scenario. It should be noted that the insulation levels corresponding to the 2010 and 2015 requirements were included only to show how the findings were affected by the space-heating demand of the reference. With the nearly ideal building components assumed in the present study, these should not be taken as reflecting realistic insulation levels for buildings constructed in accordance with 2010 and 2015 requirements.

2.4. Evaluation of thermal comfort for the reference scenario

From the thermal comfort indices shown for the reference scenario in Fig. 5, it can be seen that there are a number of critical zones in each house. One is the kitchen/living room in Case A (Zone 6), where it was difficult to achieve sufficient daylighting during overcast conditions due to the room depth. Another critical room in this house is the southeast-oriented bedroom on the 1st floor (Zone 2), where daylighting was only just met and the only transmission area is the large south-facing roof surface and a small wall facing east. However, for such zones with solar-exposed roof, it can be seen that increased insulation thicknesses in the roof generally improved comfort. In Case B, the most critical room is Zone 6 with transmission only through the roof and ground floor.

With a standard maximum air change rate for venting of 3 h^{-1} [24], these critical zones had between 150 and 170 h with temperatures exceeding 26°C every year. However, if doubling the venting rate or evaluating the comfort in accordance with the ATC model, none of the zones had more than 100 h per year with excessive temperatures (see Fig. 5). Thus, thermal comfort criteria were met following the approach suggested in Section 2.2.

2.5. The examples of roof window improvements #A-E

A number of realistic options for improving the roof windows (#A-E in Fig. 6 and Tables 2 and 3) were selected for investigation. These range from improvements in the frame and junctions (#B) or the glazed part (#C) alone, to changes that reduced heat losses in all three components at once (#D). #A was included to represent the effect of removing the solar-control coating on all solar exposed glazing. Moreover, an improvement (#E) whereby the g-value was increased to more than 0.5 by allowing a higher heat loss coefficient of the glazing (U_g) was included for Case A.

The improvements of the glazed part (#C) were composed on the basis of already existing 2- and 3-pane glazing, to be able to define the changes in the glazing parameters as realistically as possible.

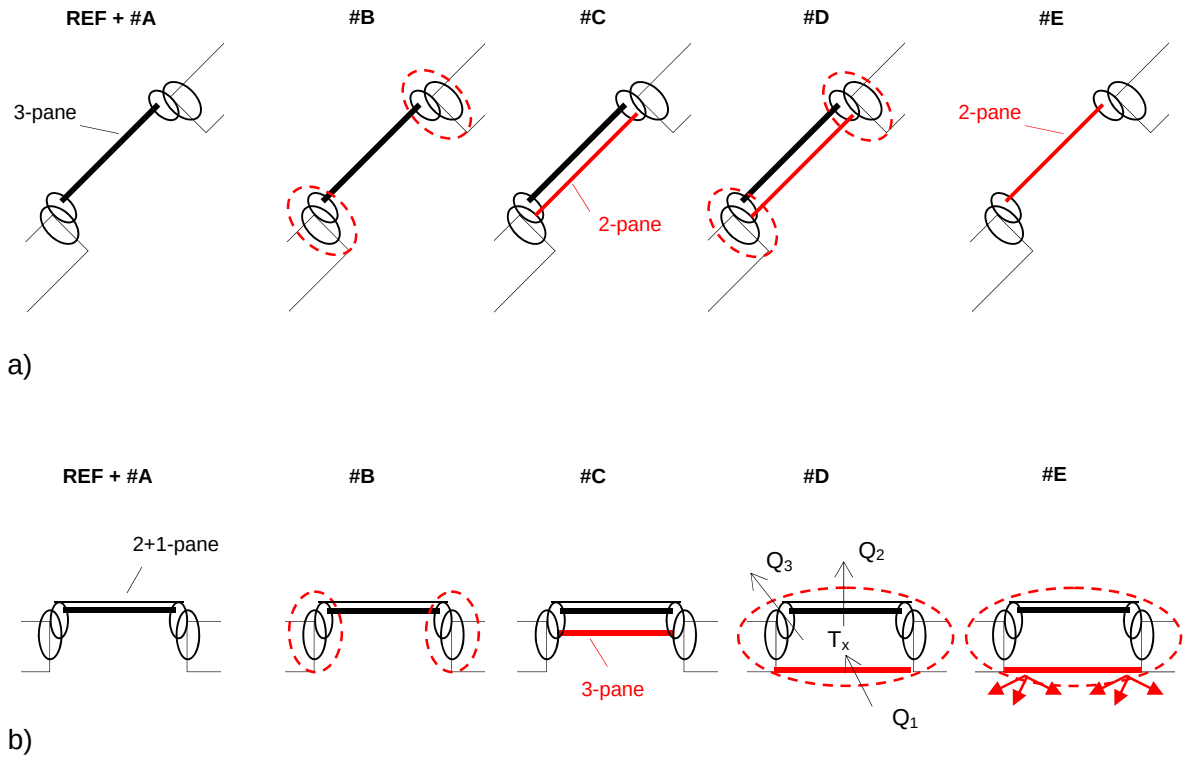


Figure 6: Sketch of the options for improving the roof windows investigated for Case A (top) and Case B (bottom), indicating the heat balance approach used to estimate the thermal properties of glazing and frame when adding the 3-pane glazing at the bottom of the light well in Case B (#D and #E).

Glazing sizes were always adjusted in accordance with the changes in light transmittance to maintain sufficient daylighting, using the following scaling factors extracted from Table 5:

- 1.24, when moving from LT 70% to 55% in Case A.
- 1.32, when moving from LT 70% to 50% in Case B.
- 0.89, when moving from LT 70% to 78% in Case A.

Frame width was always kept constant when changing the glazing size. This decreased the contribution from frame and junctions per area when increasing the glazing size, which improved the total heat loss coefficients (such as U_g' in Tables 2 and 3).

For the sloped roof windows in Case A, the combined improvement (#D) is similar to an already existing product tested in passive houses, but not yet commonly available. For the horizontal roof windows in Case B, which do not necessarily have to be openable, the combined improvement (#D) was taken further to a solution with a 3-pane glazing added at the bottom of the light well. The heat loss coefficient of this improvement was estimated using the heat balance approach sketched in Fig. 6, which assumes that all heat loss of frame and junctions would pass through the light well.

This option also offered the potential of improving the daylight distribution in the rooms by letting the pane added at the bottom of the light well transmit daylight diffusively (#E). The effect of this diffuse transmittance was found to depend strongly on room size and layout, ranging from no effect in Zone 8, to improvements in daylighting corresponding to that found with 10% higher LT in Zone 1 and 2% higher LT in Zones 6 and 9. This meant that the glazing area of the roof windows in Zones 1, 6 and 9 could be decreased to the area needed with LT 60% and 52% respectively.

2.6. Determining the scope for investment

The scope for investing in improved roof windows was determined based on the insulation costs saved by installing the improved roof windows instead of the current best standard-practice solutions. The average cost I_{ins} per surface area of increasing the insulation thickness in walls, roof or ground floor by 1 cm was estimated to EUR 1.613/(cm m^2) excluding VAT, based on the prices used by the Danish Building Research Institute in a study of cost-optimal energy use in homes [10].

2.6.1. Simplified estimation for small improvements

The scope for investing in a roof window improvement with small impact on the space-heating demand can be estimated with reasonable accuracy by multiplying the energy saved by installing the improvement ΔE_{win} by the cost of saving 1 kWh/m^2 by increasing the insulation for the reference scenario. The insulation costs saved in EUR per m^2 improved roof window A_{win} are then:

$$\textit{Saved insulation costs} = \left(\Delta E_{win} \cdot \frac{I_{ins} \cdot A_{ins}}{\Delta E_{ins}}\right) / A_{win} \tag{1}$$

where ΔE_{ins} is the energy saved at building level by increasing the insulation thickness in all constructions by 1 cm (see Table 4) and A_{ins} (411 m^2 for Case A and 573 m^2 for Case B) is the surface area of the constructions after subtraction of roof and façade window area (see Tables 1-3).

2.6.2. Direct calculation based on the insulation not needed

For the specific roof window improvements #A-E, the scope for investment was found directly by comparing the cost of the insulation needed before and after installing the improvements. The insulation costs saved in EUR per m^2 improved roof window were then:

$$\textit{Saved insulation costs} = \frac{(V_{ins\ ref} - V_{ins\ impr}) \cdot I_{ins} \cdot 100}{A_{win}} \tag{2}$$

where $V_{ins\ ref}$ is the volume of the insulation needed in the reference scenario and $V_{ins\ impr}$ is the volume of the insulation needed with the improved roof windows.

The insulation thicknesses needed with improved roof windows were found using the procedure in Section 2.3, and changes in window size were taken into account when calculating the volumes.

2.6.3. Considerations on the differences in lifetime

The lifetime of the roof window is part of the development of a competitive product and may also differ for the various components of the window, so for transparency, the scope for investment presented throughout this paper does not include any corrections for differences in lifetime between window and insulation. Instead the scope for investment is presented directly as the savings in insulation costs defined above, which will then have to cover any necessary replacements of glazing and/or window as a whole within a time frame corresponding to the lifetime of insulation. Assuming that the lifetime of the building envelope is 40-60 years [10], the lifetime of the insulation and the window construction could be fairly similar, whereas sealed glazing units may have to be replaced 1-2 times. The savings in insulation costs will therefore typically have to be divided by two or three to find the competitive price of the improvement per area for the final window product.

2.7. Further modelling assumptions

2.7.1. Daylight simulations in DAYSIM

Daylighting was evaluated based on a sensor point grid with a 0.2 m mask width positioned 0.85 m above floor (or stair) height. The grid covered only useful floor space in the houses with a height-to-ceiling of at least 1 m. For simplicity, all daylight simulations assumed wall and roof thicknesses of 0.45 m and 0.7 m respectively, irrespective of insulation level, and no external obstructions were taken into account. Surface reflectance was 70% for walls and ceilings, 80% for roof window light wells, and 30% for floors.

2.7.2. Thermal simulations in EnergyPlus

The properties of glazing and frames were modelled in EnergyPlus using the simple glazing material method [28]. The houses were modelled using internal dimensions as the transmission areas, and most rooms were modelled as separate zones (see Figs. 1 and 2), neglecting heat and air flows between zones. The basic infiltration rate was assumed to be the same in all zones irrespective of their contact to the outdoor environment (see Table 1), while infiltration rates reflecting the actual heat losses through cold bridges were inserted for each zone individually. Comparison of the EnergyPlus simulations with simulations in the standard-practice software used in Denmark for documenting the energy performance of buildings (BR15) showed very similar results, as long as the individual zones were modelled separately in both programs.

2.7.3. Weather data

Weather data from the Danish Reference Year [29] were used for both types of simulation.

3. Results and discussion

3.1. The effect of changes to the individual glazing parameters

Fig. 7 (columns 1-3) shows the effect of changes to U_g, g-value and LT (glazing size), one at a time, for the two houses, when using the scenarios with the best standard-practice roof windows with and without solar-control coating as the reference (see definition of 'REF g 0.4' and 'REF g 0.5' in Fig. 3). For Case A, either 4.8 m^2 south-oriented glazing (1st row) or 5.0 m^2 north-oriented glazing (2nd row) was changed, and for Case B, 6.1 m^2 horizontal glazing was changed (3rd row).

The effect of changes to U_g presented in this part could also be used to estimate the effect of changes to the thermal performance of the window in general, if the heat loss of frame and junctions is treated as projected onto the glazed part of the window, via the total heat loss coefficient U_g'.

Since an improvement will often consist of reductions or increases in all three parameters at once, the right-hand column in Fig. 7 shows the minimum and maximum U_g/g-ratios for which a set of simultaneous changes in the parameters will lead to energy savings. These include the effect of LT, assuming that LT will change by the same amount or double as much as the g-value (X = 1 or 2), and are defined as follows:

- Minimum U_g/g-ratio ($|\mathrm{d}g\ -0.1\ +\ \mathrm{X}\ \cdot\ \mathrm{dLT}\ -10\%|/\ |\mathrm{d}U_g\ -0.1|$) for an improvement in U_g to compensate for the simultaneous decreases in g-value and LT (black curves).
- Maximum U_g/g-ratio ($|\mathrm{d}g\ +0.1\ +\ \mathrm{X}\ \cdot\ \mathrm{dLT}\ +10\%|/\ |\mathrm{d}U_g\ +0.1|$) for an improvement in g-value and LT to compensate for the simultaneous increase in U_g (grey curves).

The lower the minimum U_g/g-ratio and the higher the maximum U_g/g-ratio, the easier it is to find a set of changes that improves the energy consumption of the glazing.

The large dotted curves without markers indicate the relative importance of improvements to U_g and g-value without considering the effect of LT ($\mathrm{d}g\ +0.1/\ \mathrm{d}U_g\ -0.1$).

Comparison of the U_g and g-value alone (1st and 2nd column in Fig. 7) shows that the effect of changes to the g-value decreased more rapidly with space-heating demand than the effect of changes to U_g. For the scenario with solar-control coating in Case B (REF g 0.4), the savings in space heating resulting from increasing the g-value from 0.4 to 0.5 (grey curve, 2nd column) were reduced by 50% when going from the least insulated building to the building consuming nearly zero-energy. In comparison, the savings from decreasing U_g by 0.1 W/m^2 K (black curve, 1st column) were reduced by 17%. As a result, improvements to the g-value went from being 4.1 times to being only 2.5 times as important as improvements to U_g for the horizontal glazing in Case B (see the large dotted line in the right-hand column). For the south-oriented sloped glazing in Case A, the same relationship changed from 5.0 to 3.4 (and from 3.2 to 2.3 for all roof glazing in this house in total).

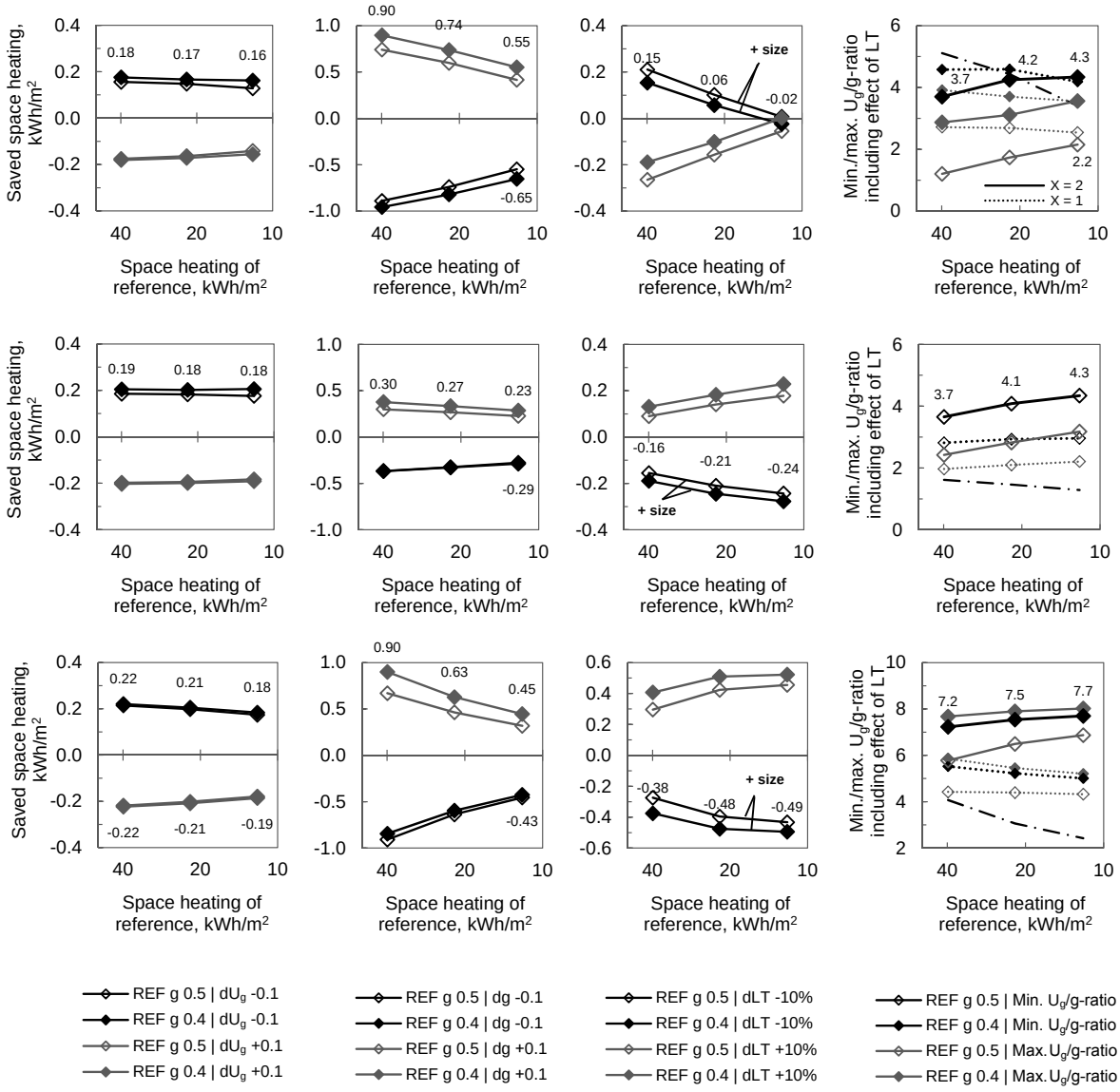


Figure 7: Effect of changes to U_g, g-value (g) and LT (glazing size) for south- and north-oriented roof window glazing in Case A (1st and 2nd row), and for the horizontal roof window glazing in Case B (3rd row). The minimum U_g/g-ratio ($|\mathrm{d}g\ -0.1 + \mathrm{X} \cdot \mathrm{dLT}\ -10\%|/\ |\mathrm{d}U_g\ -0.1|$) and the maximum U_g/g-ratio ($|\mathrm{d}g\ +0.1 + \mathrm{X} \cdot \mathrm{dLT}\ +10\%|/\ |\mathrm{d}U_g\ +0.1|$) for a set of simultaneous changes in the parameters to save energy are shown in the right-hand column. These include the effect of LT, assuming that LT changes by the same amount or double as much as the g-value (X = 1 or 2). The larger dotted line shows the relative importance of improvements to U_g and g-value, excluding the effect of LT ($\mathrm{d}g\ +0.1/\ \mathrm{d}U_g\ -0.1$). This line and the data labels refer to REF g 0.4 for horizontal and south-oriented glazing and to REF g 0.5 for north-oriented glazing.

With the decreasing ability of the houses to utilise solar gains, the effect of LT (glazing size) changed when going from the highest to the lowest space-heating demand as well (3rd column):

- For the roof windows in Case A facing south, increased glazing size changed from being a way of saving energy to having almost no effect on space heating.
- For the horizontal roof windows in Case B and the roof windows in Case A facing north, increased glazing size led to considerably more space heating with all insulation levels.

If we look at the minimum U_g/g-ratios (black curves) needed for an improvement in U_g to compensate for the simultaneous reductions in both LT (increased glazing size) and g-value, these were considerably higher than the ratios found for the U_g and g-value alone. Moreover, they hardly changed at all with insulation level due to the changing effect of window size (LT) and g-value superseding each other. For improvements in the two houses consuming nearly zero-energy, where LT decreased by twice as much as the g-value (X = 2), these ratios were:

- Case A: Minimum U_g/g-ratio of 4.3 (for both orientations).
- Case B: Minimum U_g/g-ratio of 7.7.

The effect of changes to the g-value was however not linear. For solar-exposed roof glazing in both houses (Fig. 7, top and bottom rows), the energy savings from increasing the g-value to above 0.5 (grey curves without fill-in) were 25-30% lower than if the g-value was increased from 0.4 to 0.5 (grey curves with fill-in). This is in line with previous studies [3-7], which found that the effect of increasing the g-value diminished after certain values. As a consequence, the energy savings from increasing the g-value to above 0.5 could compensate for only smaller increases in U_g, which lead to the following maximum U_g/g-ratios for such improvements (grey curves without fill-in):

- Case A: Maximum U_g/g-ratio of 2.2 (south) and 3.2 (north).
- Case B: Maximum U_g/g-ratio of 6.9.

In comparison with the minimum U_g/g-ratios identified above, these ratios are rather small.

The lower utilisation of solar gains and larger consequences of increased glazing size found for Case B than for Cases A may be due to the less-insulated window used as a reference in this house and the larger heat losses for horizontal roof windows than for sloped roof windows. Moreover, zones with roof windows in Case B consumed approximately 11 kWh/m^2, which is considerably less than the space heating consumed by zones with roof windows in Case A (see Tables 8 and 9).

Table 8: Space-heating demand distributed over zones for the reference scenario with nearly zero-energy consumption for Case A. Zones with roof windows are marked with '*'.

Zone		Space-heating demand (kWh/m^2)	Gross floor area [1)] (m^2)
1	Activity, stairs, etc. S/N *	11.1	35.2 (0.76)
2	Bedroom S/E *	12.9	14.0 (1.00)
3	Bedroom N/E *	22.2	14.0
4	Bathroom N *	38.3	7.6
5	Large bedroom S/N/W *	17.3	26.2 (0.43)
6	Kitchen/living room S/W	2.7	58.7
7	Bedroom S/E	8.8	17.0
8	Utility room N/E	16.4	15.1
9	Bathroom N	12.0	10.6
10	Bedroom N/W	16.7	15.0
Zones with roof windows		16.8 [2)]	96.9
Other zones		8.0	116.3
Total		12.0	213.2

1) Fraction of roof window area in zone facing south is given in brackets.
2) Of this, zones with south-oriented roof windows consumed around 13 kWh/m^2 and zones with north-oriented roof windows around 21 kWh/m^2.

Table 9: Space-heating demand distributed over zones for the reference scenario with nearly zero-energy consumption for Case B. Zones with roof windows are marked with '*'.

Zone		Space-heating demand (kWh/m^2)	Gross floor area (m^2)
1	Kitchen/living room S/W *	8.5	83.0
2	Bedroom (S)/E	14.5	17.2
3	Bedroom E	8.6	15.5
4	Bedroom E	8.6	15.5
5	Bedroom (N)/E	16.7	14.6
6	Storage/ activity (-) *	16.3	10.1
7	Utility room N	14.4	14.3
8	Large bedroom W *	12.4	23.2
9	Bathroom W *	19.1	10.3
10	Bathroom N/W	24.6	9.5
Zones with roof windows		10.7	126.6
Other zones		13.9	86.5
Total		12.0	213.2

3.2. The effect of the examples of roof window improvements #A-E

Fig. 8 (left-hand side) shows the energy savings at building level from replacing the best standard-practice roof windows in the reference scenario with the improved roof windows #A-E. The scope for investing in the improvements per area of improved roof window (as defined in Section 2.6.2) is shown to the right. The same figure also shows in brackets average changes to insulation thicknesses and changes to thermal comfort in the most critical zones, after the houses have been insulated for the same energy consumption as before. Fig. 9 shows thermal comfort for all relevant zones.

3.2.1. Removed solar-control coating (#A)

Removing the solar-control coating on solar-exposed glazing (#A), corresponds to the maximum change in g-value that can typically be achieved without affecting the U_g or LT of the glazing. This improvement led to savings in space-heating demand of 0.6 kWh/m^2 in both houses, which is slightly more than the savings achieved for the best of the thermal glazing improvements considered in this study. However, while all the other improvements provided similar thermal comfort as for the reference scenario, this improvement considerably increased the time with excessive temperatures (Figs. 8 and 9). The insulation costs of approximately EUR 200 saved by removing the solar-control coating would therefore have to cover the installation and maintenance of dynamic solar shading devices or other supplementary means to avoid overheating.

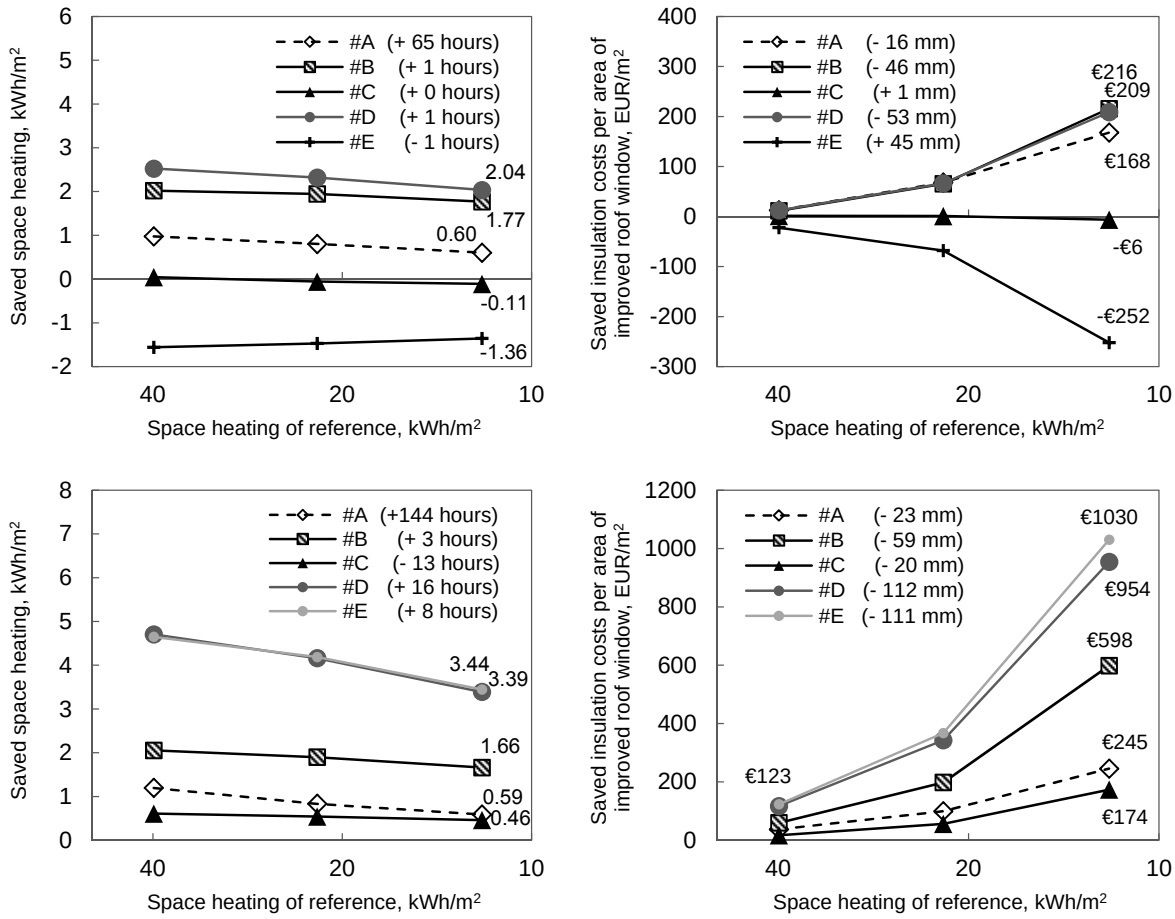


Figure 8: On the left: Savings in building space-heating demand from replacing the roof windows in the reference scenario with the improved roof windows #A-E for Case A (top) and Case B (bottom). Changes in the number of hours with operative temperatures exceeding the adaptive thermal comfort limit are shown in brackets for the most critical zones (Zones 1 and 6). On the right: The insulation costs saved per area of improved roof window, with the average reduction in insulation thickness due to the improvements indicated in brackets.

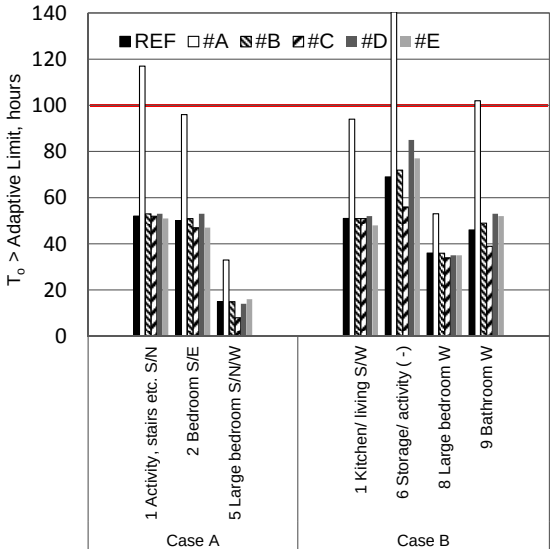


Figure 9: Hours with operative temperatures exceeding the adaptive thermal comfort limit in zones with solar-exposed roof windows for the reference scenario (REF) and for the scenarios with improved roof windows (#A-E). All scenarios are insulated to comply with the nearly zero-energy target for space heating and the venting rate is 3 h^{-1}.

3.2.2. Thermal improvements to the glazing (#C)

The thermal improvement in the glazing in Case A (#C) turned out almost neutral. An estimate based on Fig. 7 (see Section 3.1) would reveal that the minimum U_g/g-ratio for such an improvement to save energy (when X = 1.5) is: $(0.65 + 0.29 + 1.5 \cdot 0.02 + 1.5 \cdot 0.24)/(0.16 + 0.18) = 3.9$, which equals the U_g/g-ratio of 3.9 for the improvement (see changes in g-value and U_g' in Table 2). The considerably better improvement for Case B (U_g/g-ratio of 8.7), on the other hand, led to savings in space-heating demand of 0.5 kWh/m^2, which is reasonable with the minimum U_g/g-ratio of 7.7 for this improvement found in Section 3.1.

The improved glazing in Case B led to savings in insulation costs of approximately EUR 170 per area of improved roof window. Assuming two replacements of sealed glazing units throughout the lifetime for insulation, the improved window may cost EUR 50-60 more per m^2 than the windows that are standard practice today. A similar scope for investment could have been achieved by using this improvement in Case A, where the energy saving potential would be approximately the double, while the costs of saving energy by means of insulation would be almost the half (see Section 3.4).

3.2.3. Glazing with higher transmittances? (#E−Case A)

If we look at the 2-pane glazing in Case A (#E), the increase in g-value of this improvement could not compensate for the 8 and 19 times larger increase in U_g, and it considerably increased space heating. According to Fig. 7 (see Section 3.1), the U_g/g-ratio for this type of improvement to save energy should have been at most 1-2 or 4, which could not have been achieved even if the solar-control coating on south-oriented glazing had been removed.

3.2.4. Improved frame and junctions (#B)

The largest energy savings were achieved when reducing heat losses through frames and junctions. The improvement of frames and junctions alone (#B), which corresponded to changes in U_g' for the inserted glazing of 0.52 W/m^2 K for Case A and 0.83 W/m^2 K for Case B (see Tables 2 and 3), led to energy savings of 1.7-1.8 kWh/m^2 in the two houses. This reduced insulation costs per area of improved roof window by around EUR 200 in Case A and EUR 600 in Case B, which would probably have to cover at most 1 replacement if sealed glazing units can be replaced separately.

3.2.5. Combined improvements (#D)

The combined improvement in Case A (#D) shows the effect of improving the frame and junctions (#B) and the glazing (#C) at the same time. From Fig. 8 it can be seen that this resulted in slightly more energy savings than when improving the frame and junctions alone (#B), even though the improvement in the glazing itself (#C) was found to have neutral or slightly negative effect on space heating. This means that the improvement in the glazing had a positive effect on space heating when combined with the improvement in frame and junctions, due to the way the consequences of increased glazing size decreases with improved thermal properties (see Section 3.3). The scope for investment (EUR 200) per area of improved roof window, however, did nearly not change because the savings were distributed onto a larger window area (see Table 2).

The combined improvement in Case B (#D) shows the effect of adding a 3-pane glazing at the bottom of the light well, which reduced heat losses through frames and junctions to almost one fifth of those found for the reference window (see the specific heat loss in Table 3). This reduced space-heating demand by 3.4 kWh/m^2, which is twice the energy saved by improving the frame alone (#B), even though the frame construction itself was not changed. On average, this relatively simple improvement would save the building owner more than 100 mm insulation in all constructions and reduce the insulation costs by EUR 950 per area of improved window. If this amount has to cover at most two replacements, the improved roof window could cost up to at least EUR 310-320 more per m^2 than the windows that are best standard practice today and still compete with the investment in 100 mm more insulation.

3.2.6. Glazing with diffuse transmittance (#E−Case B)

If replacing the glazing added at the bottom of the light well in Case B with a 3-pane glazing that transmits daylighting diffusively (#E), slightly less glazing area was needed for sufficient daylighting in Zones 1, 6 and 9. This led to slightly improved thermal comfort (see Figs. 8 and 9) and a scope for investment of EUR 80 more per m^2 improved window than for #D. This exemplifies a permanent approach for improving thermal comfort beyond what can be achieved with solar-control coating.

3.3. Derived effects of installing improved roof windows

Fig. 10 (left-hand side) shows the effect of increasing the glazing sizes to more than needed for sufficient daylighting for the reference window and for the examples of improved windows #A-E. Before increasing the glazing size, the scenarios with improved roof windows were insulated to have the same energy consumption as the reference scenario. The results show that space-heating demand increased less when increasing the glazing size for the improved roof windows than for the reference window. This means that improved roof windows would make it cheaper for building owners to use larger windows in combination with dynamic solar shading or other means to avoid overheating. Furthermore, it means that improvements in the glazed part (that involve reduced LT) will perform better the larger the overall improvement. Fig. 7 would therefore tend to underestimate the energy saving potential of thermal improvements in glazing, frame and junctions combined (such as #D).

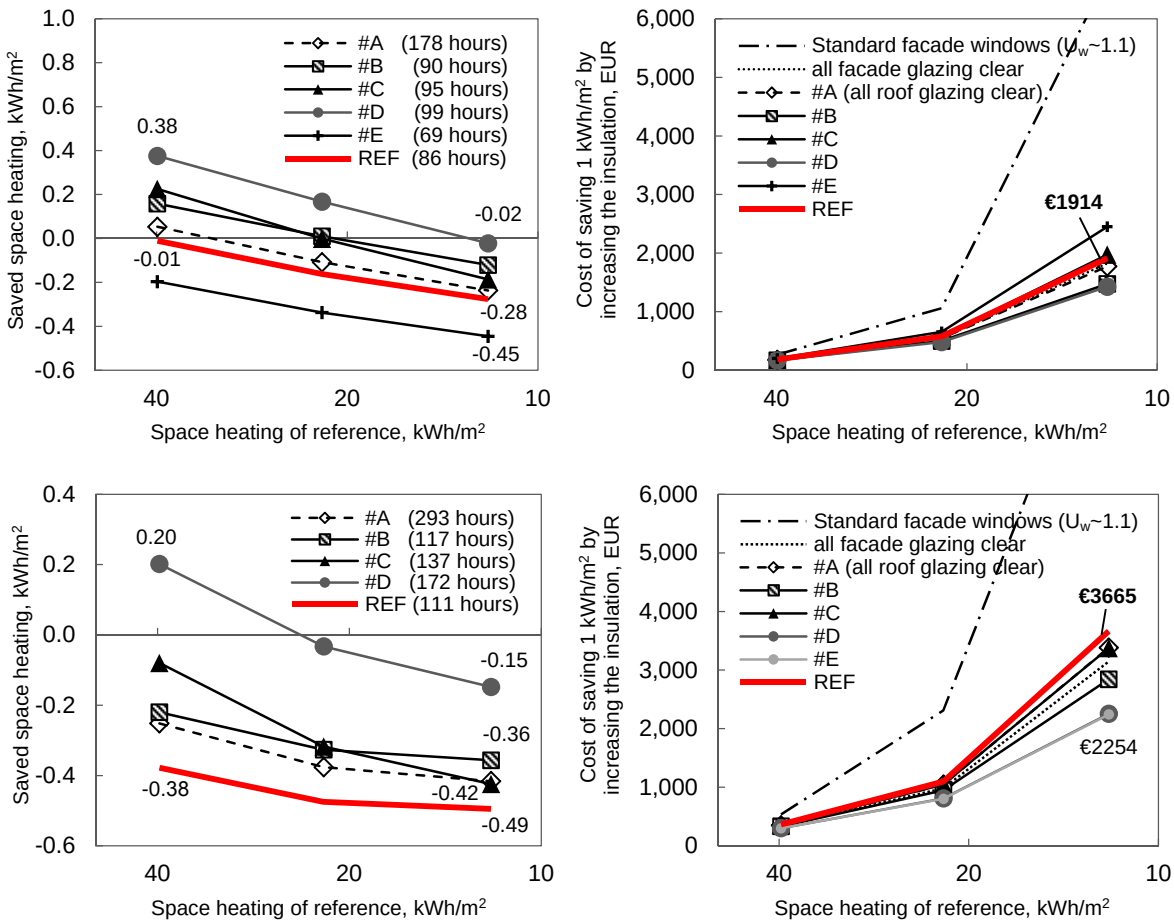


Figure 10: On the left: The effect on space-heating demand of increasing the window sizes corresponding to LT −10%. On the right: The cost of saving 1 kWh/m^2 by means of insulation. Case A (top) and Case B (bottom). The results are shown for the reference scenario and for scenarios with the improved roof windows. The number of hours with operative temperatures exceeding the adaptive thermal comfort limit after increasing the glazing area is shown in brackets for a venting rate of 3 h^{-1}.

3.4. Sensitivity of the scope for investment

Fig. 10 (right-hand side) shows the costs at building level of saving 1 kWh/m^2 by increasing the insulation thicknesses for the reference scenario and for the scenarios with improved windows #A-E, as presented in Section 3.3. These costs are also shown for a scenario without solar-control coating on the façade windows and for a scenario with less optimal façade windows.

3.4.1. Sensitivity to changes in assumptions

From Fig. 10 it can be seen that removing the solar-control coating on all roof or façade glazing would have made the costs of saving energy by means of insulation for the houses only slightly lower than for the reference scenario. Such changes to the reference scenario would therefore not have affected the scope for investment significantly. If using less optimal façade windows, on the other hand, the costs of saving energy were more than doubled. This illustrates how rather small deviations from the optimal building components assumed could easily increase the scope for investment significantly, which indicates that the savings in insulation costs identified throughout this paper may be considered rather conservative estimates of the scope for investment.

3.4.2. Sensitivity related to application

For minor improvements, such as #A and #C, it can be seen that the costs of saving 1 kWh/m^2 by increasing the insulation is only slightly lower than for the reference scenario. The scope for investing in such improvements could therefore with reasonable accuracy be estimated by multiplying the energy saving potential of the improvements with the costs of saving 1 kWh/m^2 by means of insulation, as suggested in Section 2.6.1.

For larger improvements, however, such estimations should be used with care. For example, if we multiply the energy savings for improvement #D in Case B by the EUR 3665 needed for the reference scenario to save 1 kWh/m^2 by increasing the insulation, the savings in insulation costs would be estimated to $(3665 \cdot 3.39)/10.8 =$ EUR 1150 per m^2 improved roof window, which is EUR 200 more than found directly through simulation. Similarly, if using the EUR 2254 needed to save 1 kWh/m^2 by means of insulation for the scenario with the improved window (#D), the savings in insulation costs would be underestimated by approximately EUR 250.

4. Conclusions

From the part showing the effect of changes to the heat loss coefficient (U_g), the solar heat gain coefficient (g-value) and the light transmittance (LT) of the glazing, one at a time, we found that the utilisation of solar gains decreased when lowering the space-heating demand of the houses, while the consequences of reducing LT (increasing glazing size) increased. Due to these two tendencies superseding each other, the minimum U_g/g-ratios needed for an improvement in U_g to compensate for the simultaneous reductions in both g-value and LT, hardly changed with space heating.

For the two houses consuming nearly zero-energy, a thermal improvement of the glazing led to energy savings if:

- U_g decreased by 4.3 times as much as the g-value in Case A.
- U_g decreased by 7.7 times as much as the g-value in Case B.

These relationships assume that LT will as a maximum decrease by twice as much as the g-value.

Increasing the g-value to above 0.5 (by allowing a higher U_g), could at most compensate for 2-3 and 7 times larger increases in U_g for Case A and B respectively.

From the specific roof window improvements investigated in the second part, we found the following examples of reduced insulation costs in the houses per m^2 improved roof window:

- EUR 170 in Case B for thermal improvements in the glazing (#C). The energy saving at building level was 0.5 kWh/m^2. A similar scope for investment would be expected in Case A.
- EUR 200 in Case A and EUR 600 in Case B for improvements in frame and junctions (#B). The energy savings at building level were 1.7-1.8 kWh/m^2 for the two houses.
- EUR 950 in Case B for a simple combined improvement (#D), where the addition of a 3-pane glazing at the bottom of the light well extensively reduced heat losses through glazing, frame and junctions, all at once. The energy saving at building level was 3.5 kWh/m^2.

The final scope for investment due to the savings above will depend on the lifetime of the products. The windows as a whole may, for example, have to be replaced once and the glazing components twice throughout a period corresponding to the lifetime of insulation (40-60 years). In comparison with the roof window products that are best standard practice today, users would then be able to pay:

- EUR 50-60 more per m^2 window with improved glazing (#C).
- EUR 100-300 more per m^2 window with improved frame and junctions (#B).
- At least EUR 320 more per m^2 window with the 3-pane glazing added in the light well (#D).

5. Outlook

These findings show a large potential for improvements in frame and junctions, that we strongly recommend roof window manufacturers to consider. At the same time, results in this study showed that increased glazing size would increase space-heating demand less the better the overall energy performance of an improvement. An improvement in the glazed part would therefore typically perform better in combination with improvements in frame and junctions than alone. Furthermore, it should be noted that the examples of improvements in glazing, frame and junctions presented in this study are based on well-known existing technology, so it is likely that experts will come up with much better options when looking into the possibilities in more detail.

The reduced insulation costs identified throughout this paper show an increasing potential for making improved roof windows available at prices that are less than the prices that would currently be paid to meet near future energy requirements by means of insulation. For every 1 kWh/m^2 saved at building level by improving the roof windows, the insulation costs in the houses were reduced by EUR 1914 in Case A and EUR 3665 in Case B, and these amounts were most likely on the conservative side, due to the optimal building components generally assumed in the houses.

Finally, this study showed how the thermal improvements in glazing, frame and junctions investigated supported an approach where daylighting and thermal comfort criteria were met without the use of more advanced means than well-dimensioned windows for daylighting and solar-control coating on south/east/west-oriented and horizontal glazing. If such competitive roof window products can be made available, this would make it cheaper for users to construct nearly zero-energy homes, and these homes could be designed for sufficient daylighting and thermal comfort throughout in a fairly easy way as well.

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References

[1] European Union, Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings (recast), Official Journal of the European Union, 18/06/2010, Strasbourg, France, 2010.

[2] Inanici, M.N., Demirbilek, F.N. Thermal performance optimization of building aspect ratio and south window size in five cities having different climatic characteristics of Turkey. Building and Environment 35 (2000) 41-52.

[3] Persson, M-L., Roos, A., Wall, M. Influence of window size on the energy balance of low energy houses. Energy and Buildings 38 (2006) 181-188.

[4] Vanhoutteghem, L., Svendsen, S. Modern insulation requirements change the rules of architectural design in low-energy homes. Renewable Energy 72 (2014) 301-310.

[5] Skarning, G.C.J., Svendsen, S., Hviid, C.A. Investigation and description of European buildings that may be representative for "nearly zero" energy single family houses in 2020. Proceedings of the CISBAT Conference, Lausanne, 4-6 September 2013, 247-252.

[6] Vanhoutteghem, L., Skarning, G.C.J., Hviid, C.A., Svendsen, S. Impact of façade window design on energy, daylighting and thermal comfort in nearly zero-energy houses. Energy and Buildings 102 (2015) 149-156.

[7] Skarning, G.C.J., Hviid, C.A., Svendsen, S. Roadmap for improving roof and façade windows in nearly zero-energy houses in Europe. Energy and Buildings 116 (2016) 602-613.

[8] Meier, A. What is the cost to you of conserved energy? Harvard Business Review 61 (1) (1983) 36-37.

[9] Meier, A. The cost of conserved energy as an investment statistic. Heating, Piping and Air Conditioning 55 (9) (1983) 73-77.

[10] Aggerholm, S.O. Cost-optimal Levels of Minimum Energy Performance Requirements in the Danish Building Regulations, Danish Building Research Institute, Aalborg University, 2013.

[11] Danish Transport and Construction Agency, Building Regulations 2015 Ver. 01.07.2016, 2016, http://bygningsreglementet.dk/br15_01/0/42 (accessed 20.10.2016, in Danish).

[12] Jaber S., Ajib, S. Thermal and economic windows design for different climate zones. Energy and Buildings 43 (2011) 3208-3215.

[13] Karabay, H., Arıcı, M. Multiple pane window applications in various climatic regions of Turkey. Energy and Buildings 45 (2012) 67-71.

[14] Hansen, S., Vanhoutteghem, L. A method for economic optimization of energy performance and indoor environment in the design of sustainable buildings. Proceedings of the 5th International Building Physics Conference, IBPC2012, Kyoto, Japan, 28-31 May 2012, 741-747.

[15] Foldbjerg, P., Asmussen, T. Using ventilative cooling and solar shading to achieve good thermal environment in a Danish Active House. The REHVA European HVAC Journal 50 (3) (2013) 36-42.

[16] Du, J., Hellström, B., Dubois, M.-C. Daylighting Utilization in the Window Energy Balance Metric: Development of a Holistic Method for Early Design Decisions, Lund University, 2014.

[17] Du, J. Window systems and energy performance in one-family houses: Size and shading effects. Proceedings of the Building Simulation and Optimization Conference, London, 23-24 June 2014.

[18] US Department of Energy, EnergyPlus Energy simulation software, http://apps1.eere.energy.gov/buildings/energyplus/ (accessed 15.07.2015).

[19] Zhang, Y., Korolija, I. Performing complex parametric simulations with jEPlus, in: SET2010 – 9th International Conference on Sustainable Energy Technologies, 24-27 August 2010, Shanghai, China.

[20] Zhang, Y. 'Parallel' EnergyPlus and the development of a parametric analysis tool, in: IBPSA BS2009, 27-30 July 2009, Glasgow, UK, 1382-1388.

[21] DAYSIM, Advanced daylight simulation software. http://daysim.ning.com/ (accessed 15.07.2015).

[22] European Standard EN 15251. Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics, 2007, CEN.

[23] Petersen, S. Daylight conditions and thermal indoor climate in low-energy homes – the consequence of Danish building code. Proceedings of 7th Passivhus Norden, Sustainable Cities and Buildings, Copenhagen, 20-21 August 2015.

[24] Aggerholm, S.O. and Grau, K.E. SBi-anvisning 213: Bygningers energibehov – Beregningsvejledning, 3rd edition, Danish Building Research Institute, Aalborg University, 2014 (in Danish).

[25] IESNA, LM-83-12, IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE), New York, NY, USA, IESNA Lighting Measurement, 2012.

[26] Mardaljevic, J., Christoffersen, J. A roadmap for upgrading national/EU standards for daylight in buildings. Proceedings of the CIE Centenary Conference, Paris, 15-16 April 2013, 178-187.

[27] Mardaljevic, J., Christoffersen, J. 'Climate connectivity' in the daylight factor basis of building standards. Building and Environment 113 (2017) 200-209.

[28] Arasteh, D., Kohler, C., Griffith, B. Modeling Windows in Energy Plus with Simple Performance Indices. Report LBNL-2804E, Lawrence Berkeley National Laboratory, October 2009.

[29] Jensen, J.M., Lund, H., Design Reference Year, DRY – et nyt dansk referencer. Technical Report lfv-281, Technical University of Denmark, 1995 (in Danish).