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Solar Architecture of Low-Energy Buildings for Industrial Applications

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***Abstract*—**This research focuses on the optimization of glazed surfaces and the assessment of possible solar gains in industrial buildings. Existing window rating methods for single windows were evaluated and a new method for a simple analysis of energy gains and losses by single windows was introduced. Furthermore extensive transient building simulations were carried out to appraise the performance of low cost polycarbonate multi-cell sheets in interaction with typical buildings for industrial applications. Mainly energy saving potential was determined by optimizing the orientation and area of such glazing systems in dependency on their thermal qualities. Moreover the impact on critical aspects such as summer overheating and daylight illumination was considered to ensure the user comfort and avoid additional energy demand for lighting or cooling. Hereby the simulated heating demand could be reduced by up to 1/3 compared to traditional architecture of industrial halls using mainly skylights.

***Keywords*—**Solar Architecture, Passive Solar Building Design, Glazing, Low-Energy Buildings, Industrial Buildings.

I. Introduction

PASSIVE solar building design has become a key word in architecture for residential and office buildings during the last decades. For such buildings many studies as [1] or [2] exist regarding solar design. Anyway there still seems to be a lack of design tools as also indicated in IEA-SHC Task 41 – "Solar Energy and Architecture" [3]. In the field of energy saving in industrial buildings in general very little research such as [4] - [8] exists. And analyses or studies for optimized glazed surfaces design in such buildings are still missing.

The aim of passive solar design is to gain more usable solar energy through windows than being lost through them during the heating period. Similarly summer gains must be reduced to avoid overheating in the hot season. Therefore in dwellings large heat-absorbing double and triple glazing on the south side combined with removable sunscreens has become widely spread. Often the glazing is also covered by overhangs, which shade the windows in summer when the sun stands high, but leave beam radiation inside the building on winter days when the sun´s incident angle is low.

In industrial buildings such solar design methods are still not applied in the current architecture. Also high performance glazing, or complex façade systems with movable shadings as e.g. discussed in [9] and [10] are much too costly and often not applicable. Thus low cost solutions such as multi-cell polycarbonate sheets shall be checked for their suitability in low-energy industrial halls. The high potential of such polycarbonate panels for various energy saving solutions was already shown in [11].

Besides the glazing quality, the orientation of the glazed surface is deciding for its energy performance. Due to large building dimensions, warehouses and production buildings are often illuminated by horizontal roof openings such as domelights, light-bands or skylights. This is to illuminate the building based on a small window surface. Unfortunately the here used material cannot keep up with the mentioned high performance components for dwellings. Their U-values are still in a low range and even the legal requirements e.g. for the reference building of the German building regulations [12] are still low for such components. Moreover almost no shading solutions for industrial roof openings are available yet. Besides, the intensity of radiation in winter is significantly higher on south façades, than on the usually flat roofs of industrial buildings. Fig. 1 shows the monthly averaged intensity of radiation dependent on the orientation for typical German climate (Meteonorm climate data for Potsdam). It indicates that not only solar radiation in the cold months December and January can be almost doubled by choosing south oriented vertical openings instead of horizontal roof openings, but also that summer overheating can hereby be reduced.

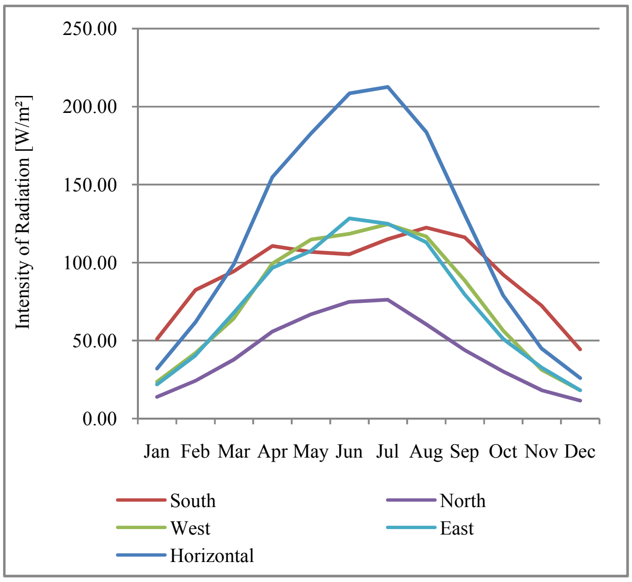

Fig. 1 Intensity of radiation for different orientations in Potsdam

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II. Energy Performance of Single Windows

The thermal performance of glazing is described by two parameters, the U-value and the solar heat gain coefficient (SHGC) or g-value. While the U-value indicates the thermal losses the g-value describes the solar heat gains through a glazing irrespective of their usability. Having two parameters makes it difficult to assess the window quality and energy performance and even to compare window qualities with those of other building components just characterized by U-values.

Thus window energy rating systems (WER) were applied in some countries which rate solar gains and heat losses in one value. An overview is given in [13] and [14]. Most of these methods follow the approach of (1) while not all include the heat losses by air infiltration.

$$E_{Ref} = A \cdot g_W - B \cdot (U_W + L) \quad (1)$$

where:
E_{Ref} = Energy index (positive values are gains) [kWh/(m²a)]
A = Factor for solar gains based on climatic conditions
B = Factor for heat losses based on climatic conditions
g_W = Solar heat gain coefficient [-]
U_W = Thermal transmittance of the total window [W/m²K]
L = Heat losses by air infiltration [W/m²K]

The factors A and B are defined individually for each country based on typical heating degree days and sun hours. Denmark e.g. will also set limiting values for the energy index of windows for the future. Roof -and skylights will need a positive balance in 2015 while other windows have to meet this goal in 2020 [15].

To give an overview about how diverse the same components can behave in different countries/climates according this rating method, some results are displayed for European countries having applied this rating method (Fig. 2).

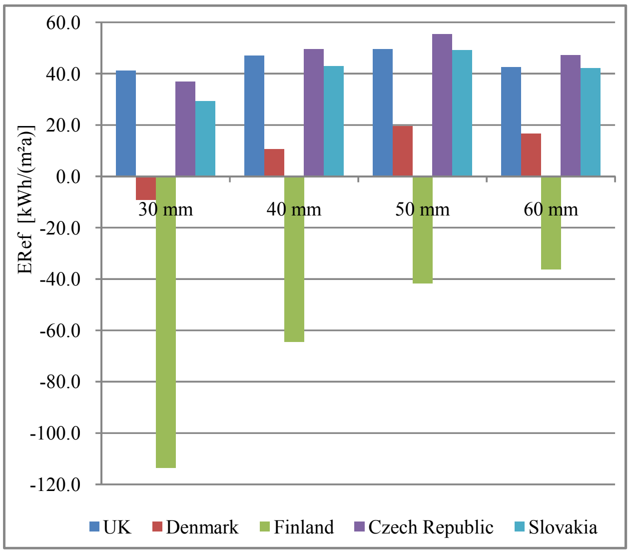

Fig. 2 Performance of Polycarbonate sheetings in different climates

The rating in Fig. 2 was carried out for different multi-cell polycarbonate sheetings typically used as low-cost solutions in the industrial building sector. Their thermal characteristics are shown in Table I. All glazing systems in Fig. 2 have a negative performance in Finland while all others except the 30 mm sheetings have a positive balance in all other countries.

TABLE I
Characteristics of Analyzed Polycarbonate Sheets and Typical Glazing

Glazing	U [W/m²K]	g [-]
30 mm PC sheet, 3 cells	1.60	0.69
40 mm PC sheet, 6 cells	1.10	0.56
50 mm PC sheet, 9 cells	0.87	0.50
60 mm PC sheet, 11 cells	0.75	0.43
Double glazing (Low-e)	1.02	0.63
Triple glazing (Low-e)	0.65	0.50

The yearly balance approach according to (1) assumes that it is not important at what time in the heating period the solar gains occur. But with an increasing use of renewable energy which is not always constantly available, also the occurrence time along the year should be a criterion. But most important is that it is not distinguished between different orientations of the window. A window may have a positive energy balance on the south side but a negative balance on the north or west side. Thus the WER-method is just useful to compare different windows but not to rate the real yearly energy performance of a window. Furthermore it is not possible to use the Energy index E_{Ref} for a direct comparison between windows and other building components. But a method to compare them is required as windows and walls/roofs are actually competing components. To decide if the glazed surface in a wall shall e.g. be raised for energy saving reasons, it is crucial to have a comparable characteristic.

Hence a monthly based assessment of the total window performance shall be introduced here. This rating is also comparable to the U-value of opaque components (e.g. walls and roofs) as it has the same unit [W/m²K]. The net heat losses of a window considering both thermal losses and solar gains are calculated by (2). As the solar gains are continuously fluctuating these values are averaged for each month in the heating period. Therefore and as the solar transmittance is dependent on the changing incident angle of the sun, the solar energy transfer through a window is determined by transient simulations using the software TRNSYS. For this purpose hourly climate data was used.

$$U_{net,m} = U_g - \frac{q_{solar,m}}{\theta_{i,m} - \theta_{e,m}} \quad (2)$$

$$q_{solar,m} = g \cdot (0.84 \cdot I_{diffuse} + I_{beam} \cdot \sqrt{\cos\alpha}) \quad (3)$$

where:
$U_{net,m}$ Average net heat losses of a window during a particular month (U-value equivalent) [W/m²K]
$q_{solar,m}$ Solar gains during a particular month [W/m^2]
U_g U-value of the glazing [W/m²K]

$\theta_{i,m}$ Monthly averaged inside temperature [°C]
$\theta_{e,m}$ Monthly averaged ambient temperature [°C]
g Solar heat gain coefficient [-]
$I_{diffuse}$ Diffuse solar radiation on the window [W/m²]
I_{beam} Beam solar radiation on the window [W/m²]
α Incidence angle of solar radiation on the window [°]

This approach also allows considering different inside temperatures which are often significantly lower in industrial buildings than in dwellings. The impact of the inside temperature on the energy performance of a window is visible in Figs. 3 and 4. These results based on (2) and (3) show the average net heat losses of south oriented vertical windows during the heating period from October until March (Potsdam climate, Fig. 1). The characteristics are based on Table I.

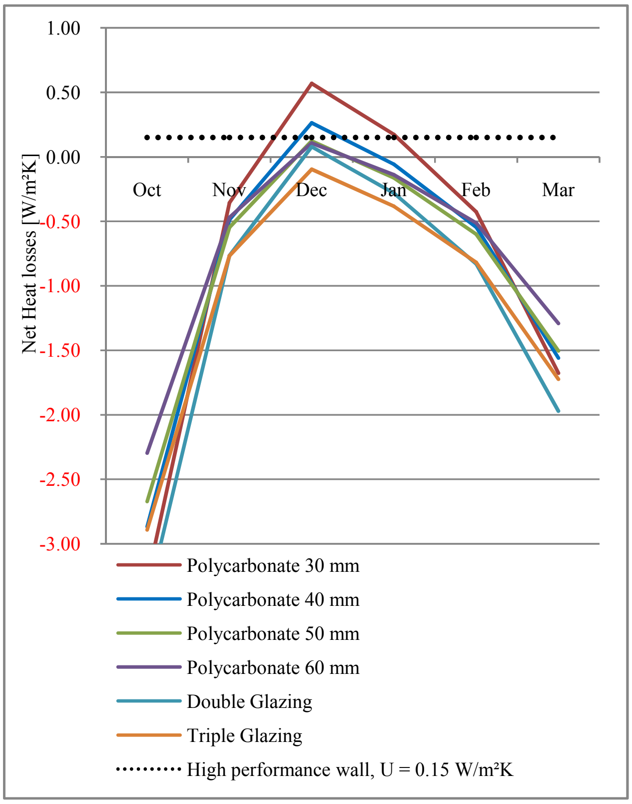

Fig. 3 Performance of south oriented glazing (see Table I) θ_i = 20°C

For the lower inside temperature (12°C), which is typical for many warehouses, all glazing systems have a positive energy balance during the whole year according to this rating. For the higher inside temperature (20°C) all analyzed products except the triple glazing have net heat losses in December.

The better performance of low heated buildings is in general due to the effect that the thermal heat losses are lower but the solar gains almost remain the same. Further it is visible that even low-cost polycarbonate sheetings can reach a better energy performance in middle European climate than a highly insulated wall.

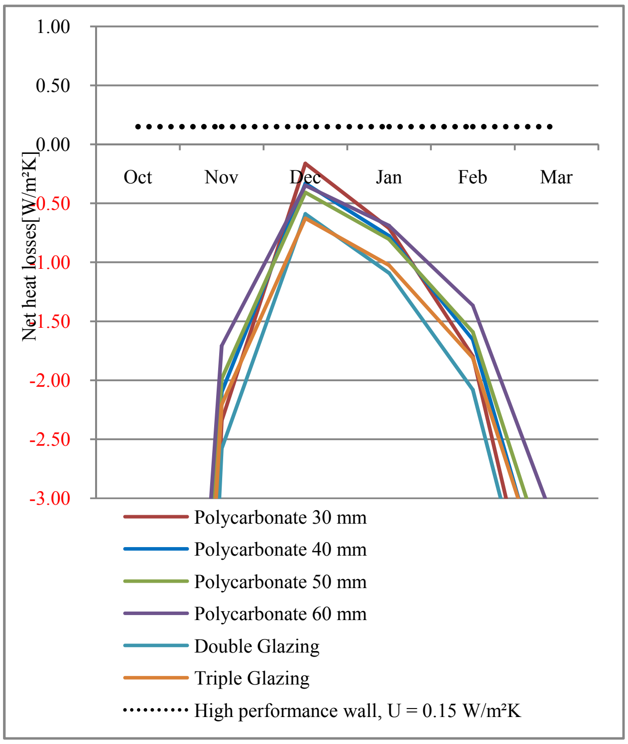

Fig. 4 Performance of south oriented glazing (see Table I) θ_i = 12°C

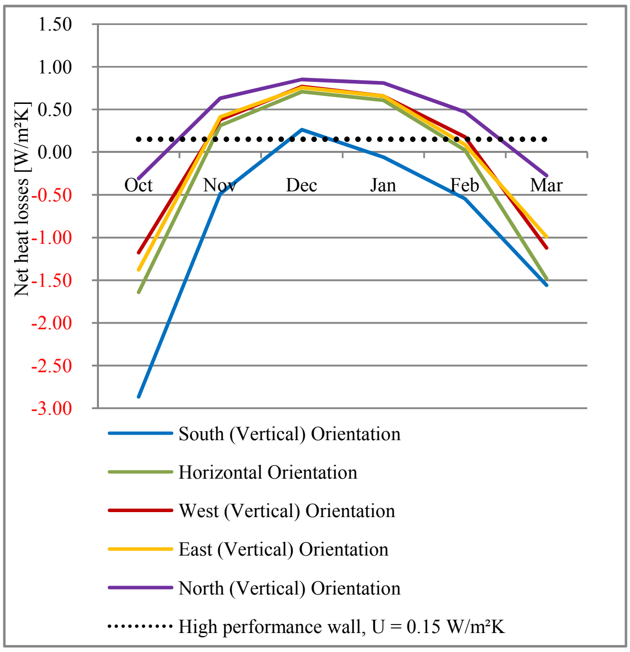

Fig. 5 Performances for different orientations, 30 mm PC, θ_i = 20°C

This is unfortunately only valid for the south façade and of course only if the glazing is not shaded. As shown in Fig. 5 the net heat losses for all other facades are significantly higher in the cold season. The north orientation of course shows the worst performance while the west and east orientation as well as the horizontal orientation have similar losses.

III. Yearly Energy Performance of the Total Building

Both presented methods, the WER-method (1) and the new introduced monthly method (2), (3) just rate the quality of the single window. But they do not consider the interaction between the window and the building. This is very important as solar gains even in winter are only useful if heating is required at the same time. Hence the first installed square meters glazing area in a building will have another impact than a completely glazed façade. Thus transient building simulation (TRNSYS) was used to assess not only the glazing quality but the impact of glazed surfaces on the total building performance. Therefore an industrial light steel structure building (l x w x h = 65 m x 30 m x 8 m) was simulated while the glazing quality and area were variegated. The thermal quality of the envelope was with intent chosen of high quality to represent future standards with a short heating period ($U_{wall} = U_{roof} = 0.20$ W/(m²K), $U_{slab} = 0.35$ W/(m²K)).

For the required heating demand of industrial buildings it is very important how big internal gains are. Those can be almost zero for a warehouse without any machines and little labor demand, but gains can also reach up to 200 W/m² for a cold forming or even up to 500 W/m² for the smelting of a foundry [16]. Hence general assumptions are difficult, but energy saving buildings are actually more required in productions for assembling which have lower internal gains. Thus the analyses were carried out for buildings without any internal loads (e.g. warehouses) and for those having a moderate load (e.g. assembling). For these production buildings standard values of 40 W/m² (5W/m² for occupants + 35 W/m² for machines [16]) were used, also mentioned in the German energy rating standard [17]. Moreover the influence of night and weekend setbacks was important to respect, because production buildings often have a shorter usage period than dwellings.

Yearly simulation results for constant inside temperatures (12°C and 17°C) typical for warehouses are displayed in Figs. 6 and 7. It is directly visible that for these buildings the use of glazing on the south facade as well as in the flat roof both decreases the yearly heating demand significantly. Further the south oriented façade glazing shows a much better performance than skylights. For low heated buildings this effect is even stronger. Due to the shorter heating period of low heated buildings the higher winter gains of the south orientation are more important than the higher gains via skylights in spring and autumn.

If the window area is small the differences between vertical south orientation and horizontal orientation is smaller than for large glazing surfaces. This is also due to the huge solar gains in spring and autumn that are higher for skylights.

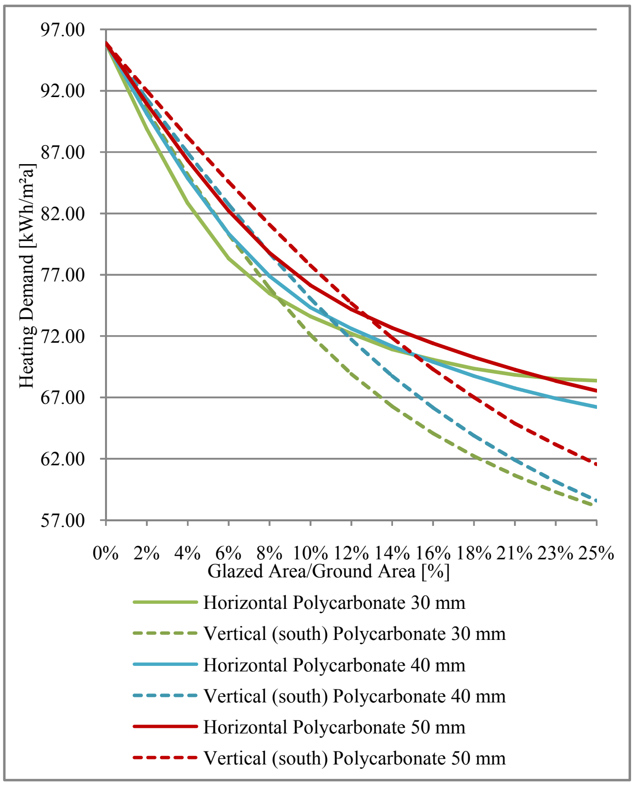

Fig. 6 Heating demand dependent on the glazing area, $\theta_i = 17°C$

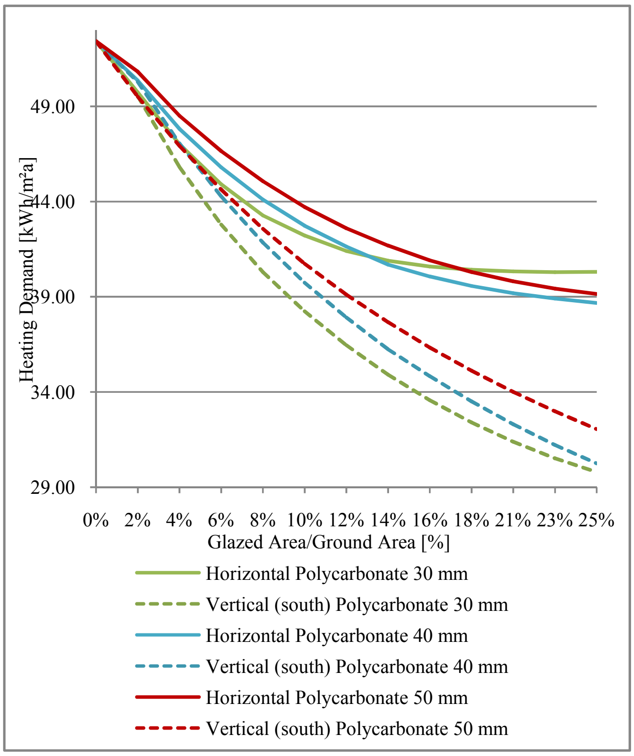

Fig. 7 Heating demand dependent on the glazing area, $\theta_i = 12°C$

Changing the window orientation from the roof to the south façade can reduce the total heating demand of a low heated warehouse by up to 25 %. Interesting is also that the 50 mm polycarbonate sheeting (9 cells) with the lowest U-value has the lowest performance and the 30 mm sheeting (3 cells) with the highest U-value has the best performance for these buildings. Here the additional layers reduce the g-value already too much (see Table I). This effect could not be clearly recognized in rating the single window without the interaction with the building (see Chapter II).

The influence of the same glazing on production buildings with internal gains and a night and weekend setback (here 4K at night and during weekend) is very different (see Figas. 8, 9). In general the internal loads of machines and the temperature setback cause a significant lower heating demand. Noticeable is further that too large horizontal glazing areas increase the energy demand again.

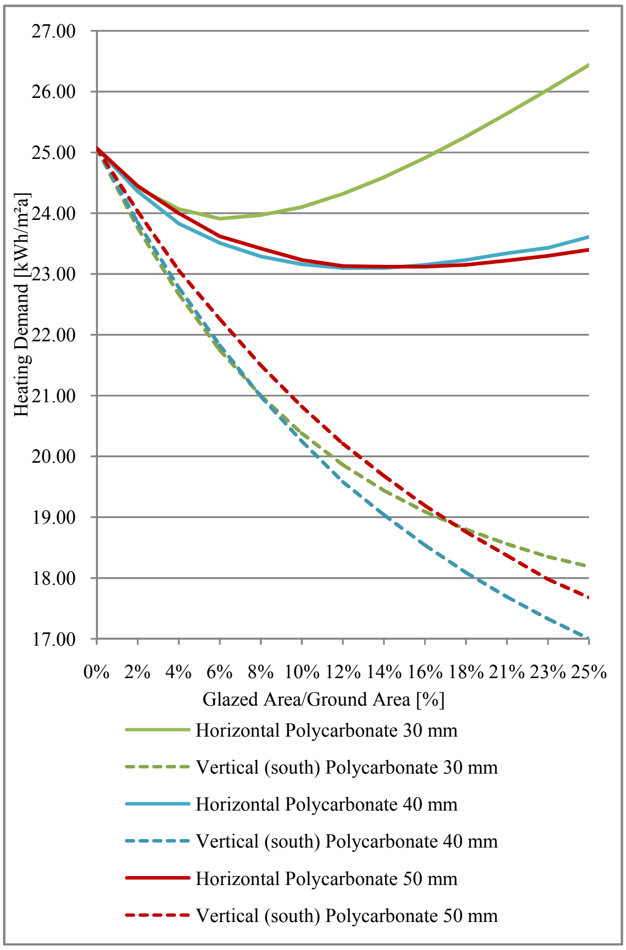

Fig. 8 Heat. demand θ_i = 17°C, night/weekend-setback, internal gains

For large skylight areas in production buildings the U-value is more deciding than the g-value. As these buildings have a constant internal gain during the operational time the high solar gains via skylights in spring and autumn are not helpful. More important is not to lose the internal gains by a low U-value. Thus the 30 mm polycarbonate glazing has a much worse performance if used horizontally than the other panels (40 mm and 50 mm). If the polycarbonate glazing is installed at the south façade large solar gains can be used in winter. Anyway here the 40 mm multi-cell sheeting shows the best performance for both internal temperatures.

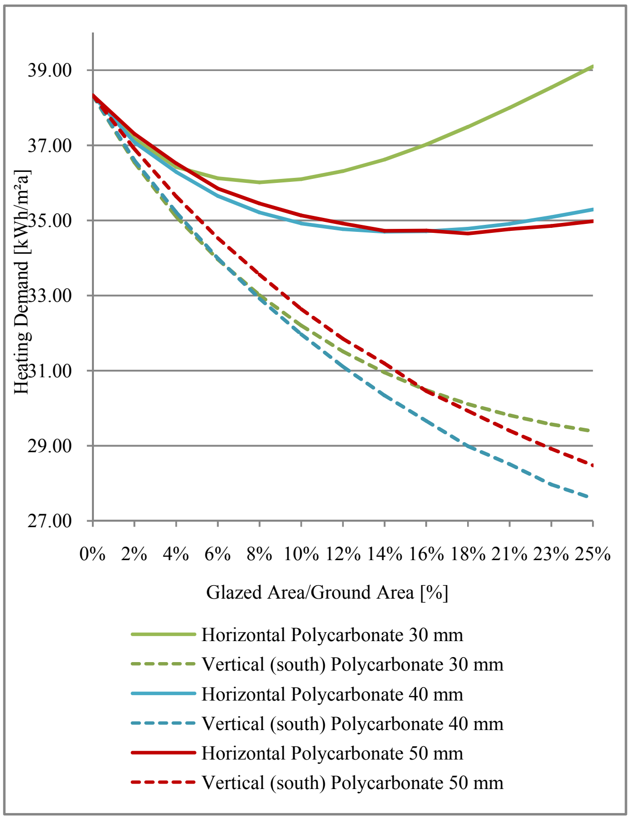

Fig. 9 Heat. demand θ_i = 20°C, night/weekend-setback, internal gains

Fig. 10 shows the performance of the 40 mm polycarbonate sheet for different climate conditions at the south facade. Here climates of the countries already used for the comparison in Fig. 2 were used. The differences between the heating demands of the same buildings in different climates are huge. Due to the high "basic heating" by the high internal gains the differences are even higher than they would be in a warehouse without any internal gains. While in Helsinki the building still has an energy demand of at least 35 kWh/m², in mild climates it can even perform below Passive House standard. Dependent on the amount of solar radiation and of the outside temperature the difference between a vertical south orientation and a horizontal orientation differs.

Further it can be said that the optimum glazing area is much different for all climates. While in Helsinki the optimum is at 6% horizontal and 25% south oriented glazing area, in London the optimum is at 25% for both horizontal and vertical orientation. In Kopenhavn having a very sunny climate the change from horizontal to vertical openings can increase the heating demand even by 40%. In general Fig. 10 shows that a climate dependent window design is essential.

All simulations do not consider shading effects by e.g. trees or buildings around the building. Thus the results energy demand can increase significantly if glazed surfaces are shaded. This always has to be considered for the solar building design.

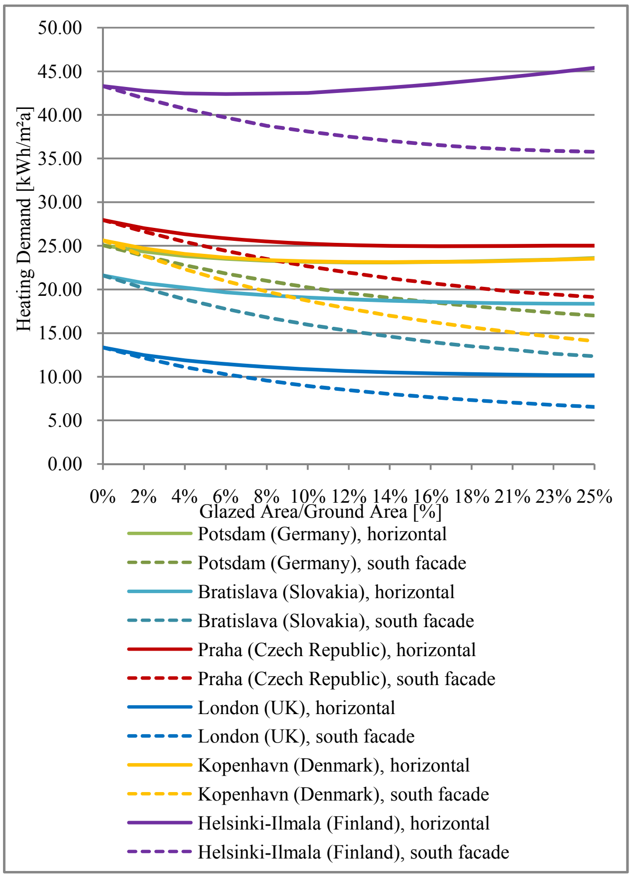

Fig. 10 Heating demand for different climates, 40 mm polycarbonate, θ_i = 17 °C (setback), internal gains

IV. Summer Overheating

In the shown simulations the glazing area was not limited by summer overheating of the building. But overheating is in general a limiting factor for designing the glazing area. Thus also simulations of the internal temperature in different industrial hall buildings were carried out. How the orientation of windows influences the summer temperature in such a steel structure building (l x w x h = 65m x 30 m x 8m) is shown in Fig. 11.

Of course the inside temperature is dependent on many parameters such as ventilation, thermal mass of the building structure and the interior etc. but here a direct comparison between vertical and horizontal glazing in the same building is shown. In this example an optimized night and day ventilation was considered.

For this rating the method for summer overheating assessment described in the German DIN 4108-2 [18] is used. According to this standard the over-temperature degrees (>26°C) are integrated for the whole year. This value must not exceed 500 Kh/a for non-residential buildings, according to the German building regulations [12].

At first glance at Fig. 11 the considerable difference between horizontal and south oriented windows is visible. Depending on the conditions the over-temperature degrees over 26°C can be up to seven times higher for roof lights than for south façade glazing. For the here demonstrated sample building the limiting value of 500 Kh/a is never reached by warehouses as they usually do not have any internal gains. For production buildings with internal gains of 40 W/m² the overheating limit is reached if the glazing in the roof exceeds 12% (30 mm PC) respectively 15% (40 mm PC) of the ground area. For south oriented façade glazing the limits are higher. Here the 30 mm sheet can reach 22% of the ground area and for glazing with a lower g-value such as the 40 mm sheet the area can even exceed 25% without reaching the limit. Thus it is evident how important window orientation is for a comfortable indoor climate and that the vertical south orientation has significant advantages.

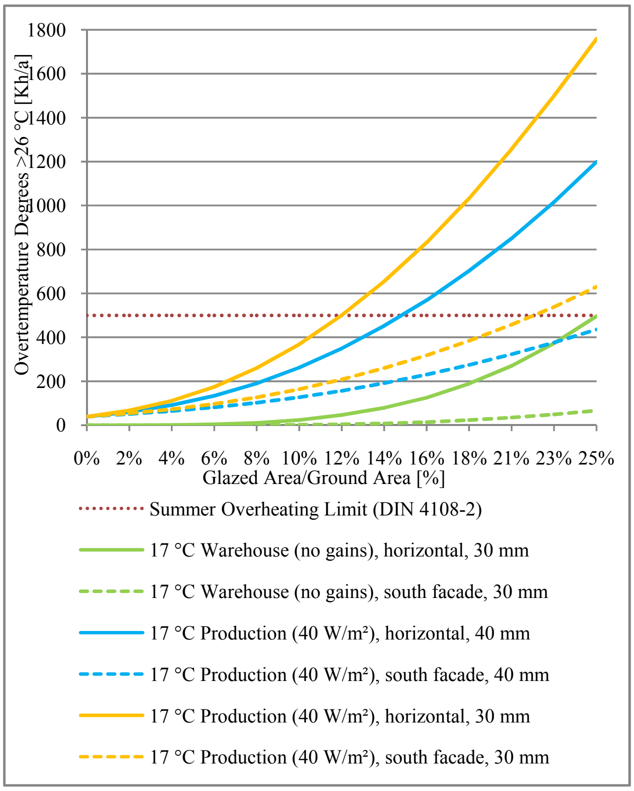

Fig. 11 Summer overheating (DIN 4108-2), 40 mm polycarbonate

Another method for rating summer overheating is suggested by Feist in [19]. Here only the frequency of overheating hours is accounted without rating the intensity of overheating. This method sets the overheating temperature at > 25°C and gives a limit of 10% overheating time compared to the usage time. Due to the short operational time in a production the results according this method are even worse and allow even smaller skylight areas.

V. Illumination of the Building

Now it was already shown that horizontal glazing in the roof should be limited as far as possible to save heat energy. But the current use of skylights in industrial roofs is for sure chosen on purpose. To well illuminate hall buildings with large dimensions it is much easier to use just enough roof openings. To see how lighting quality changes by using south façade glazing instead of roof openings, lighting simulations using the software Dialux were carried out. The assessment of daylight in a building is based on the daylight factor which is the ratio of indoor to outdoor light level described by (4) [20].

$$D = \frac{E_p}{E_a} \cdot 100\ \% \qquad (4)$$

where:
D = Daylight factor [%]
E_p = Illuminance at a point on the indoor working plane [lx]
E_a = Outdoor illuminance at the same time [lx]

Simulation results of the average daylight factor dependent on the glazing area, its orientation (south façade or flat roof) and its position in the wall are shown in Fig. 12. For the simulations the glazed surface was positioned as a light band at the top of the wall. The daylight factor is different at every place in the building as visible in Figs. 13 and 14 which show the distribution of the daylight factor in the ground plot.

Hence in Fig. 12 the minimum and the average daylight factor is given for the sample building (l x w x h = 65m x 30 m x 8m) dependent on the glazing area. The clear advantage of skylights for illumination is visible. A relatively small fraction of the ground area can be enough to reach a sufficient daylight illumination by horizontal skylights.

If the same illumination shall be reached by glazing in the south façade its surface must exceed the skylight surface by far. For example the average daylight factor caused by 25% south façade glazing is equivalent to approximately 9% skylights. Usually fractions of 9% skylight area are not exceeded in industrial buildings. Thus it seems to be possible to reach a comparable average daylight illumination with an almost completely glazed south façade for this sample building. Further the distribution of the illumination is different for the two kinds of windows. Figs. 13 and 14 show the difference of the daylight factor distribution in the building. This has also to be recognized for the architectural design and the usage of a building. The values of Figs. 12–14 are of course only valid for the dimensions of the sample building (30 m). Deeper buildings are even more difficult to illuminate just by windows in the south façade. Smaller buildings are of course easier to handle. Anyway a general rating that also includes the determination of which additional artificial lighting is required dependent on the daylight illumination would be reasonable for future research.

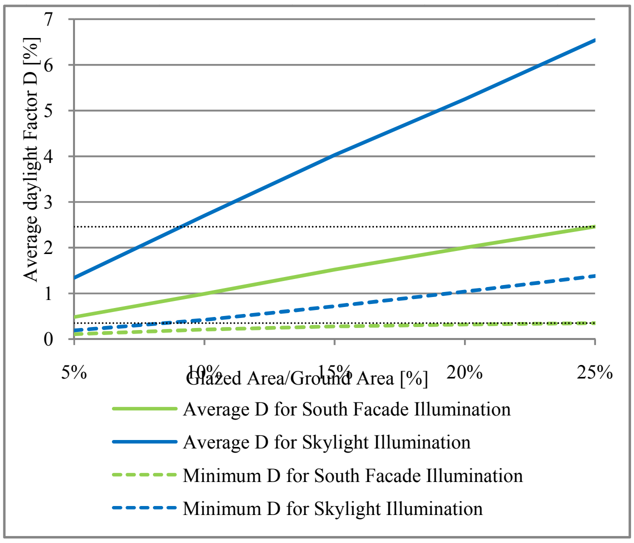

Fig. 12 Illumination quality of south facade and skylight glazing

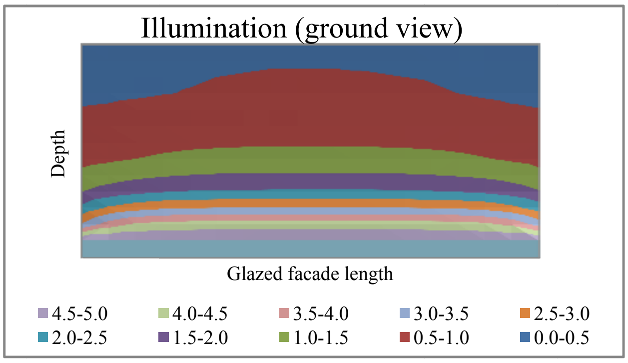

Fig. 13 Distribution of daylight factors for south façade glazing

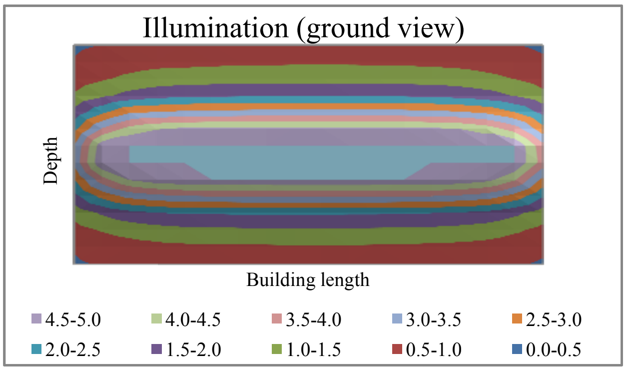

Fig. 14 Distribution of daylight factors for a ridge light dome

VI. Conclusion

The simulation results show that for heat energy saving it is usually advisable for industrial buildings to replace horizontal glazing in the roof by vertical glazing in the south façade as much as possible. If the glazing area is increased to the complete south façade of a building this can reduce the heat energy demand by up to 1/3, if the façade is not shaded. Increasing the glazing area always increases the risk of summer overheating. Therefore and as the conclusions given are only valid for the glazing simulated here, a detailed design has to be carried out for each project. Anyway the building simulations showed that using only glazing on the south façade is usually uncritical. If a sufficient daylight illumination of a building can be achieved just by a glazed south façade, depends on the dimensions and the usage of the building. Otherwise additional required electric energy for lightning has to be considered in the total energy balance of the building. In practice, combinations of south oriented windows and few roof lights seem to be a promising solution. But it is advisable to always increase the glazing in the south façade as far as possible if no significant shading must be expected.

The simulations have shown that low-cost solutions such as multi-cell polycarbonate sheets can be a reasonable alternative to expensive heat-absorbing glass especially for the industrial building sector. Further for such glazing not always the products with the lowest U-values perform the best. Polycarbonate sheets with 4-7 layers seem to be a better solution for central-European climate than sheets with more layers but a lower g-value.

Window energy rating methods seem to be only useful for the direct comparison of windows for the same usage. A real rating how windows perform in a building is not possible with such methods. To get better information about the energy performance of a window dependent on its orientation and the buildings inside temperature to allow comparison with other building components, the new rating method introduced in (2) and (3) seems to be a better possibility. Anyway the real impact on the energy demand can only be assessed by building simulations as only such transient methods are able to rate which solar gains are usable along the year. Thus for future industrial buildings the usage of elaborated building simulation methods are advisable when aspiring a solar optimized industrial hall without summer overheating. The simulation models should include surrounding buildings and trees to respect their shading impact.

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