Solar utilisation in low-energy buildings

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Abstract

For low-energy buildings, passive solar gains can contribute significantly to the heat balance. For the calculation and optimisation of the energy performance of low-energy buildings, the precise quantification of solar gains is therefore quite important. The total solar gains can be calculated from the available solar radiation and the geometry of the building. However, the relevant part of the solar gains, which is really usable to substitute heating energy, is more difficult to obtain. This part depends on the actual temperature inside the buildings, which, in turn, is influenced by the amount of solar and internal gains, heat capacity, as well as the building services. In this paper, a method is presented, to calculate the utilization of solar gains with a thermal building simulation software on a monthly basis. The results show, that for small to medium sized "passive houses" in standard German weather conditions, the utilized solar gains for the whole year is roughly (10 ± 2) kWh/(m² a), and does not depend significantly on the details of the building construction.

Introduction

Solar radiation influences the heat flux through the transparent and opaque envelope of a building. Whereas solar radiation on the opaque envelope can reduce the transmission losses, the energy flux through the glazing of windows is denoted as "passive solar gains". In low-energy buildings, passive solar gains contribute significantly to the total heat balance, consisting of heating energy, solar gains, internal gains, transmission losses and ventilation losses. Due to their time dependent and irregular availability, only a fraction of solar gains is really usable. The other part of solar gains obviously increases the indoor temperature above the desired level, i.e. it produces overheating. Purpose of this study is the accurate determination of the amount of usable solar gains, which may depend on the type of construction of the building, i.e. window type and their distribution on different orientations, effective heat capacity and heat loss coefficient or demand of heat energy, respectively. Thermal simulation methods allow to calculate both, the solar gains and the temperature distribution inside the building, by taking into account all relevant influences. The utilization of solar gains and the overheating hours are therefore calculated with TRNSYS (Klein et al., 1976). After the description of the calibrated building models, the calculation method for solar gain utilization is introduced, which is based on these models. Finally the results are presented, which are focussed on the utilized part of the solar gains for these buildings or buildings types, respectively.

Example buildings and simulation models

Four models for low-energy buildings are used, which have been calibrated against measured time series of one year length (Gieseler et al., 2003). These buildings shown in Fig. 1 and Fig. 2 represent small to medium sized low-energy buildings of different construction types. They were built between 1995 and 1998 in North-Rhine Westphalia, Germany. The

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Fig. 1: Object 1 (left): *The building in Essen-Kraienbruch, Germany, is a three story multi-family house in massive construction with basement.*
Object 2 (right): *The building in Wenden-Hünsborn, Germany, is a 1½-story single family house in wooden framework construction without basement*.

Fig. 2: Object 3 (left): *The building in Wenden-Hillmicke, Germany, is a two-family house from pre-built concrete elements with two upper floors and heated basement.*
Object 4 (right): *The building in Lindlar-Hohkeppel, Germany, is a single family house in wooden construction with two upper floors and without basement.*

outer envelope is described in Table 1, whereas the key constructional data are given in Table 2.

For the simulation of the thermal behaviour of all four buildings, the simulation software TRNSYS, version 14.2, has been used. The major part is a "Type 56" model with 8, 7, 8 and 10 zones for objects 1, 2, 3, and 4, respectively. The code of "Type 56" in our copy of TRNSYS 14.2 has been modified by us to achieve a proper edge correction for the *U*-value of windows. This modification leads to equivalent results like the window model of TRNSYS 15. The simulations are run with METEONORM weather data (Meteotest 2000). The weather data used for the current analysis are for the locations Stockholm, Trier and Milan. In Table 3, the key characteristics of the weather data are shown, i.e. the heating degree days and the total solar radiation. The simulations use a common standardised user behaviour. The total internal gains in the period September to May are 32 kWh/m² for object 1, 28 kWh/m² for object 2, and 31 kWh/m² for objects 3 and 4. The small variation is due to different occupancy, following from the details of the floor plans. The minimal infiltration rate is 0.1 ach/h. Additional window ventilation (plus 1 ach/h) and active shading by the user is only included, when the indoor temperature exceeds 24 °C. The resulting heating demand for the buildings under standardised user behaviour and different weather conditions is shown in Table 4. For typical German weather conditions, which can be represented by data for the location Trier, the buildings require heating between about 15 kWh/(m² a) and 80 kWh/(m² a). This represents the range from so called "passive houses" to today's standard (new) buildings.

Table 1: *Construction types for the outer envelope of the four objects.*

	Wall	Roof	Ground floor
Object 1	Limestone with polystyrene outside	Rafter with mineral fibre, polyurethane layer inside	Polyurethane on concrete
Object 2	wooden framework with integrated mineral fibre	Rafter with mineral fibre	Polyurethane on concrete
Object 3	Pre-built reinforced concrete elements with polystyrene outside	same as walls	Polystyrene on concrete
Object 4	Wooden monocoque construction with integrated and outside mineral fibre	same as walls	Polystyrene on concrete

Table 2: *Key constructional data and measurements*.

	Object 1	**Object 2**	**Object 3**	**Object 4**
Location (latitude, longitude, altitude)	51.46°, 7.01°, 120 m	50.95°, 7.85° 260 m	51.03°, 7.87° 250 m	51.28°, 7.39° 200 m
Finishing of construction	May 1995	June 1997	March 1998	May 1998
*A*_NHFA (net heated floor area)	403 m²	200 m²	204 m²	163 m²
*V*_air (volume of heated air)	1097 m³	600 m³	619 m³	479 m³
*A*_wall (encasing heated volume)	366 m²	196 m²	221 m²	215 m²
*A*_roof	216 m²	189 m²	130 m²	105 m²
*A*_floor	172 m²	114 m²	105 m²	101 m²
*A*_window	104.5 m²	65.0 m²	51.5 m²	45.3 m²
*U*_wall	0.24 W/(m²K)	0.23 W/(m²K)	0.13 W/(m²K)	0.10 W/(m²K)
*U*_roof	0.16 W/(m²K)	0.21 W/(m²K)	0.13 W/(m²K)	0.10 W/(m²K)
*U*_floor	0.36 W/(m²K)	0.32 W/(m²K)	0.11 W/(m²K)	0.12 W/(m²K)
*U*_window	1.6 W/(m²K)	1.3 W/(m²K)	0.8 W/(m²K)	0.8 W/(m²K)
Heating system	ground heat pump (19.7 kW heat)	district heating (max. 20 kW)	gas (4-11 kW), solar (4.8 m²), EHX (99 m)	liquid gas (2.4 kW), EHX (16 m)
Heat distribution	floor heating	floor heating	fresh air, radiators	fresh air
Control temperature for heating	room air	ambient air	extract air, room air	extract air
Heat recovery of ventilation system: *h*	exhaust only	65%	83%	90%
Air tightness: *n*_50 value	1.2 ach/h	2.0 ach/h	0.4 ach/h	0.6 ach/h
Domestic hot water	electric heating	not installed	combined with heating system	solar (7.4 m²), electric heating
Measured heating demand	**82.4 kWh/(m²·a)**	**72.9 kWh/(m²·a)**	**27.8 kWh/(m²·a)**	**9.8 kWh/(m²·a)**
Period of measurement	01.08.97 - 31.07.98	19.7.98 - 18.7.99	1.11.98 - 31.10.99	16.11.98 - 15.11.99
HDD(20/12) in measurement period	2668 Kd	4165 Kd	3835 Kd	2612 Kd
Average heating set temperature	21.5 °C	19.5 °C	20.0 °C	20.0 °C

Calculation method

The solar radiation entering the building consists of directly transmitted short wavelength radiation and heat flux from the absorbed radiation in the window. Together with the internal gains, these solar gains may at some times reduce the heating demand to zero. In such periods, the gains lead to temperatures higher than the set temperature. This occurs mostly in summer, but also in shorter periods during winter time. Due to the higher indoor temperature, the transmission and ventilation losses are increased compared to a case without solar gains. This excess of losses represents the part of the gains, which is not utilized. With TRNSYS, the utilized part of solar gains can not be calculated directly. One possibility is to calculate the heating energy demand for two simulations, one with and one without solar gains. The difference in heating energy demand defines the utilized solar gains. Note, that the proper time interval for such a study is not arbitrary. If a simulation is run without solar gains for the whole year, the transition period from summer to winter is not modelled correctly. In the summer, the building usually heats up several degrees over the set temperature. The corresponding stored heat can reduce the utilisation of solar gains in the transition period to winter. Without solar gains during summer, this effect is completely suppressed. On the other side, of course, the time interval for the simulation must be considerably longer than the time constant of the buildings, which could be up to several days. Therefore, the utilization of solar gains is calculated on a monthly basis. in this study, the year is divided into 12 months of equal length with 730 hours. This approach requires two subsequent simulations for every analysed month. After simulating a period of several weeks to guarantee independence of initial conditions, the demand of heat energy $H_0(m)$ and solar gains $S_0(m)$ are calculated for month No. m. In a second simulation over the same period of time, and under exactly the same boundary conditions, the direct and diffuse solar radiation is reduced to a smaller value or zero on all outside window glass surfaces only for month No. m (at the end of the simulation period). The solar radiation on the opaque surfaces (including window frames) is not changed. This has been achieved by a simple modification of the subroutine "DWINDOW" within the TRNSYS building model "Type 56". The resulting demand of heat and the solar gains are $H_1(m)$ and $S_1(m)$, respectively. The utilization factor h of solar gains through the transparent parts of the building is now given by the results of both simulations:

$$h(m) := \frac{\Delta H(m)}{\Delta S(m)} \equiv \frac{H_1(m) - H_0(m)}{S_0(m) - S_1(m)} \leq 1 , \quad (1)$$

with m running over all months of the heating period (usually September to May). For a complete suppression of solar radiation with $S_1(m) = 0$, the usable solar gains are given by $S_u(m) = h(m) \cdot S_0(m) = H_1(m) - H_0(m)$, which is the saving in heating demand provided by the solar radiation. For the results shown in the next section, $S_1(m) = 0$ was used for all m.

Table 3: *Characteristics of the used weather data: Heating degree days (HDD) and global solar radiation on the horizontal.*

	HDD (20/12) total year	**HDD** (20/12) September to May	**Global radiation on horizontal** September to May
Stockholm (S)	4586 Kd	4476 Kd	513 kWh/m²
Trier (D)	3505 Kd	3347 Kd	593 kWh/m²
Milan (I)	2756 Kd	2756 Kd	724 kWh/m²

Table 4: *Heating energy demand of the four objects with standardized user behaviour and without shading by the surroundings.*

	Object 1	**Object 2**	**Object 3**	**Object 4**
	Heating demand in kWh/m² for Sept. to May			
Stockholm (S)	118.9	99.7	28.1	24.6
Trier (D)	81.4	70.5	15.9	15.1
Milan (I)	61.2	49.8	9.9	8.6

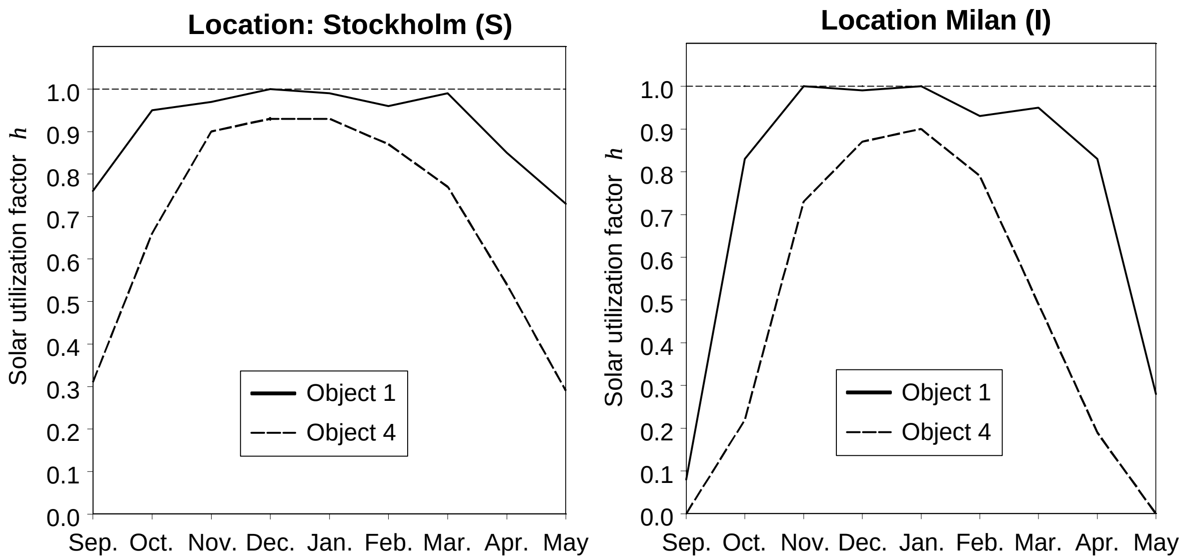

Fig. 3: *Utilisation factor of solar gains in the period September to May for the locations Stockholm (left plot) and Milan (right plot). Results for the buildings with the highest and with the lowest utilisation factors of those analysed here are displayed.*

Results

The utilisation factor h, calculated according Eq. 1, is shown in Fig. 3 for the two objects with the highest (object 1) and lowest (object 4) utilisation factor of the four analysed objects. The two plots show results for weather data representing a cold and warm European region, with all other parameters kept constant. Whereas the maximum of the utilization factor within $0.9 < h < 1.0$ for the core winter time is quite high for all buildings and both weather conditions, the utilization of solar gains varies significantly in autumn and spring. In these periods, the total gains (internal and solar) can balance the losses (transmission and ventilation), so that the heating demand is zero. This is especially valid for the high performance buildings (objects 3 and 4) and/or in warm climate (Milan), and leads to small utilization factors h or even $h = 0$.

To analyse the major influences on the utilization factor, variations of the construction type of the walls, of window size and distribution and of total heat loss have been studied. The results are presented in form of the total and utilized solar gains in the heating period, i.e. in September to May. The integration of these monthly simulation results over the heating period in Trier is shown in Fig. 4 (left side). The ratio of utilized solar gains to total solar gains is given in the figure as a percentage. The left graph shows the solar gains for the buildings in their original construction. The right graph shows the solar gains for the same buildings, but with a modified construction type of the outer opaque envelope. The originally massive buildings were changed to a light construction and vice versa. All values given in Table 2 are hereby not changed, for example the sizes and *U*-values of walls and windows remain constant. Only the type of constructions for walls, roof and ground floor (see Table 1) were interchanged between objects 1 and 2, and between objects 3 and 4. A comparison of the left and right graph in Fig. 4 shows, that the utilized solar gains do *not* depend strongly on the type of construction. The differences in utilized solar gains between the massive and the light construction type of otherwise the same building is less than 10% for all four objects and for weather data from Trier (as shown in Fig. 4), Milan and Stockholm. In general, buildings with massive construction have slightly higher utilization factor than those with light construction. The putative exemption from this rule for object 3 (see Fig. 4) is due to the shading strategy against overheating (above 24 °C). With-

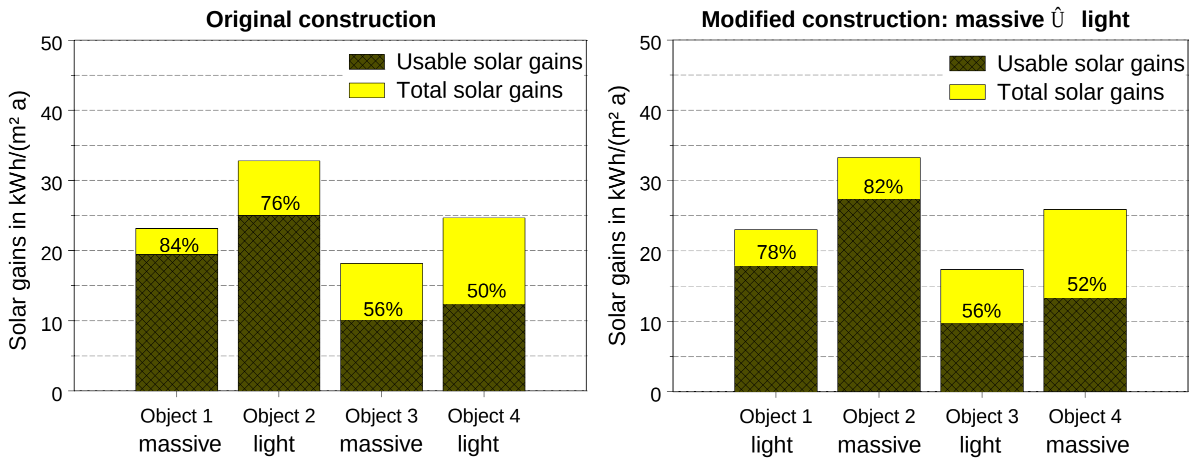

Fig. 4: *Total and usable solar gains in the period September to May. The percentage in the columns is the fraction of usable solar gains during this period. The left graph shows the solar gains for the 4 objects in their original construction. The right graph shows results for modified simulation models, where the type of wall construction has been changed from massive to light and from light to massive, respectively. Thereby, the U-values for the building envelopes were not modified.*

out active shading, the utilisation factor for the massive version is h = 55%, somewhat higher than for the light version, which in this case is only h = 53%.

Regardless of construction type, the houses with the lowest heating demand (objects 3 and 4) take advantage of significantly lower utilised solar gains than the "standard" low-energy buildings (objects 1 and 2). Note, that also the amounts of *not*-utilized solar gains are quite different for the buildings. The amount of such not-utilized solar gains gives an indication of possible overheating problems in the building. For example, object 1 requires roughly 5 times more heating than object 4, but object 4 has even more total solar gains than object 1. This results in a very low utilisation factor for object 4 and at the same time a much more significant potential overheating problem in summer. The simulation presented here, without *ambitious* shading and cooling, reveals such overheating problems. Only additional ventilation of 1 ach/h and shading of 50% is applied, if the temperature exceeds 24 °C and lasts until the temperature falls below 22 °C. A user (or an advanced sophisticated system) might be able to perform much better cooling strategies (e.g. night cooling

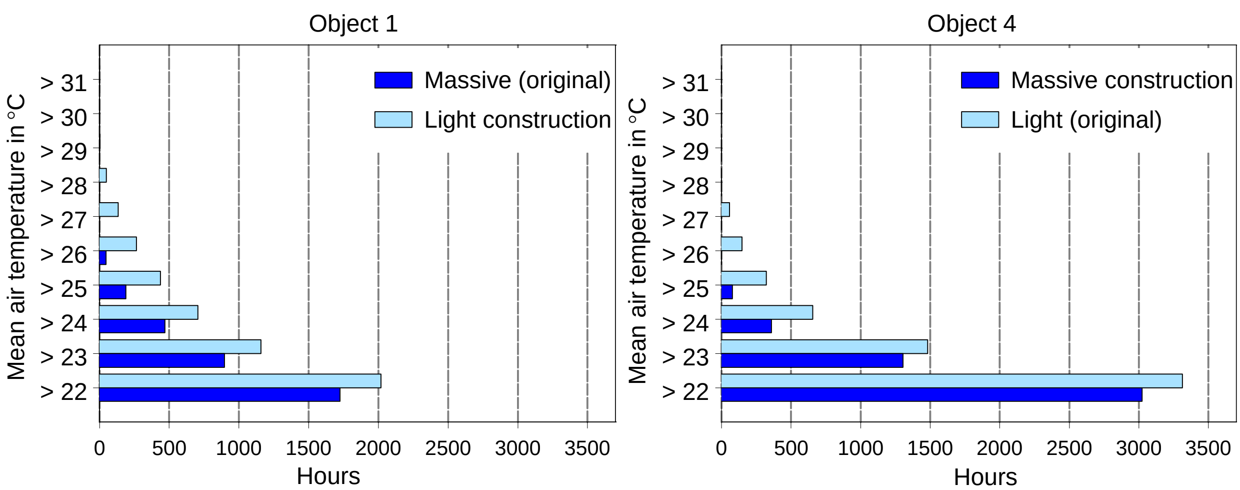

Fig. 5: *Number of hours with mean indoor air temperature above certain limits, for object 1 (left) and object 4 (right). The mean indoor temperatures are averages weighted by the volumes of the living spaces inside the buildings.*

and cooling in anticipation of hot days), however this is not always possible. In figure 5, the number of hours during one complete year with mean indoor temperature within certain temperature bands are presented for the objects 1 and 4. The object 4 exhibits significantly more overheating hours between 22 °C and 24 °C than object 1, even if its type of construction is changed from lightweight to massive.

Besides from the building mass, the major constructional differences between the 4 objects are total heat loss and window distribution. Whereas objects 2 and 4 are predominantly oriented towards south, the windows of the objects 1 and 3 are distributed equally to all directions. The influence of window size and distribution can be determined with variations of the simulation model. Exemplary results are presented in Table 5 for variations of object 3, which has originally the lowest amount of utilized solar gains compared with the other objects. In variation 1, the windows are more concentrated to the south. Variation 2 includes windows whose size is increased up to a still reasonable maximum. In variation 3, the window area is reduced to the smallest size, which is required according to the legal regulations in Germany. The results show, that the utilized solar gains for this building could be increased by about 15% (variation 2). However, due to the losses through the larger window area, the heating demand for this variation is higher than in the original case. The distribution of windows towards south (variation 1) leads to a slightly lower heating demand compared to the original construction, but this may entail drawbacks for the outside view and lighting in some zones of the building.

To emphasize the relationship between the total heat loss of the building and its utilisation of solar gains, variations of object 1 with different heat loss were simulated. The total heat loss is influenced by the thickness of the insulation layer and by the efficiency of the ventilation system to recover heat. Variations of these parameters lead to a yearly heating demand for object 1 between 124 kWh/m² to 18 kWh/m² for the period September to May and for the weather of Trier. This band of results for the heating demand is represented by 7 individual simulations, and the corresponding solar gains are shown in Fig. 6. The total solar gain is, of course, equal for these simulations, because the windows and the boundary conditions are not changed. However, the utilized solar gains decrease for decreasing heat loss, or heating demand, respectively. An additional simulation was performed for a case with heating demand as low as 9 kWh/m²a. For this case, high performance windows had to be used. These windows exhibit a lower *g*-value, which leads to lower total solar gains. Fig. 6 shows clearly, that the utilised solar gains depend strongly on the heating demand. Whereas the building with poor energy performance has used solar gains of

Table 5: *Simulation results for a variation of window size and window distribution for object 3 and weather data of Trier. The window fraction is related to the façade area.*

	Total window area	Total window fraction	Southern window area	Southern window fraction	Heating demand	Total solar gains	Utilised solar gains
					in kWh/m² for Sept. to May		
Original Construction	51.45 m²	19%	19.24 m²	28%	15.9	18.2	**10.1**
Variation 1 south dominant	50.00 m²	18%	26.81 m²	39%	14.5	19.6	**10.8**
Variation 2 large windows	60.00 m²	22%	20.62 m²	30%	17.0	20.8	**11.6**
Variation 3 small windows	30.00 m²	11%	9.14 m²	13%	14.1	10.2	**5.8**

20.0 kWh/m² this value drops for the high performance case down to 7.5 kWh/m². The reason for this is the reduced length of the heating period for high performance buildings. In such buildings, the solar gains in the transition period between winter and summer are not utilised for heating, because the heating demand tends to zero.

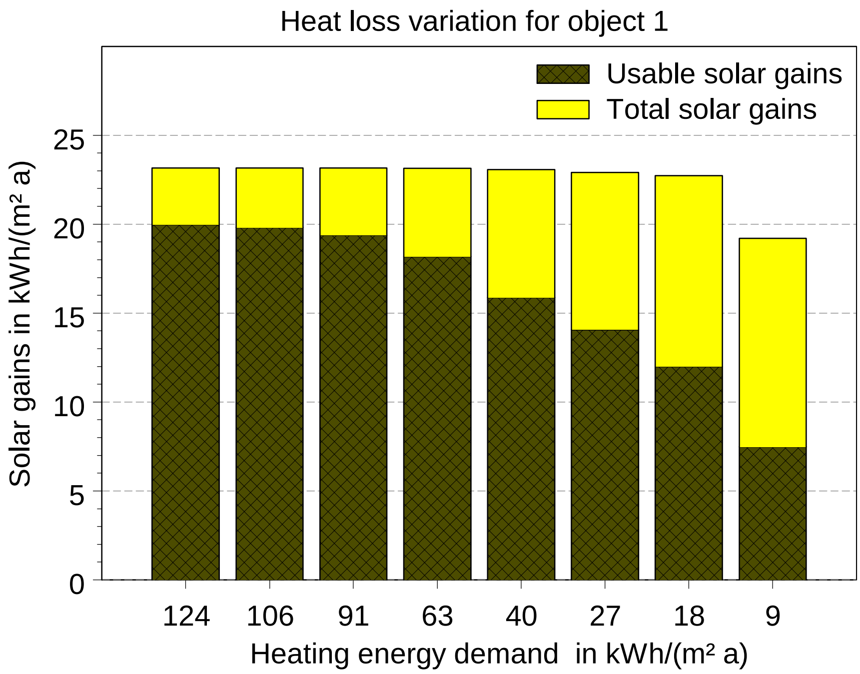

***Fig. 6:** Solar gains for variations of the insulation level of object 1. For each variation, the heating energy demand is given. For the case with heating demand of 9 kWh/(m²·a), high performance glazing (U = 0.7 W/m²K, g = 0.54) have been used. The lower g-value leads to reduced total solar gains compared to the other 7 considered cases (U = 1.4 W/m²K, g = 0.62). The simulations are performed with weather data for Trier.*

***Table 6:** Heating demand and utilised solar gains for the analysed objects and variations thereof. The heating demand is roughly 15 kWh/(m²·a) for typical German weather conditions. All these variations represent "passive houses". The weather used for the shown cases is that of Trier, if not denoted otherwise.*

	Heating demand	Utilised solar gains (S_u)
	in kWh/m² for Sept. to May	
Object 3, original construction	15.9	10.1
Object 3, variation 1 (see Table 5)	14.5	10.8
Object 3, variation 2 (see Table 5)	17.0	11.6
Object 3, original construction, weather: Milan	9.9	7.8
Object 1, variation 7 (see Fig. 6)	18.2	12.0
Object 1, variation 8 (see Fig. 6)	9.2	7.5
Object 4, original construction	15.1	12.4
Object 4, original construction, weather: Milan	8.6	11.2

For passive houses, the overall variation of the utilized solar gains is rather small. In Table 6, the heating demand and the utilised solar gains of some analysed variations of the four objects are shown. These variations represent passive houses, with a heating demand of roughly 15 kWh/(m²·a) for German weather conditions. The values for the utilised solar gains S_u shown in Table 6 can be summarised as S_u = (10 ± 2) kWh/(m² a). This range is valid for passive houses with a reasonable window fraction of about 20%. For buildings with extremely small windows or a window distribution oriented towards north, the total and usable solar gains could, of course, be smaller (e.g. variation 3 in Table 5). On the other side, in very cold climates, the utilized solar gains are larger, because of the extended heating period. In the climate of Stockholm, the utilised solar gains (and the heating demand) are up to 50% larger than for the weather of Trier. However, the dependence on construction type and window distribution is equally small for all considered climates.

Conclusions

The analysed buildings with a heating demand of about 15 kWh/(m² a) for standard German weather conditions ("passive houses") in un-shaded locations exhibit utilized solar gains of S_u = (10 ± 2) kWh/(m² a) in this climate. These solar gains do *not* depend strongly on type of construction (heavy or light) or windows, as long as the windows are reasonably in size and orientation. However, the overheating hours can increase with the window size and also depend on window orientation, especially for light-weight constructions.

Particularly for passive houses, the glazed area is extremely expensive. In conclusion, the results indicate, that for such buildings the window area towards south should *not* be maximised. Windows can be distributed over all directions and should be limited in size to provide appropriate day lighting, outside view, summer comfort and to provoke lowest costs.

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