Influence of night ventilation on the cooling demand of typical residential buildings in Germany

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ABSTRACT

The current type of construction preferred for new high energy efficient buildings in Germany, featuring highly insulated building components and an almost completely airtight building shell, raises several new challenges with regard to design, construction and use of these buildings. Cooling, in particular, is an issue that gains importance also in the residential sector, in connection with rising temperatures induced by the climate change.

Increased night ventilation is a cost-effective option to influence the indoor climate such that comfortable conditions are durably ensured, keeping technical expenditure within reasonable bounds. Though the functional principle of night ventilation is well known and its applications are manifold, it is not widely considered by building planners. One of the reasons for lacking attention might be that the potentials of night ventilation with regard to building cooling cannot be sufficiently estimated. The present study investigates the impact of night ventilation on the cooling demand of typical new residential buildings in Germany.

The potentials of night ventilation are examined for two exemplary cases, namely for a single-family home and a multi-family building. Thermal building simulation is used to perform numerical assessments and to discuss functionality and effects of natural ventilation. The study analyses several influences on the indoor thermal comfort including the impact of different types of construction, various designs, thermal insulation standards, ventilation strategies and the use of solar shading devices in combination with or without night ventilation.

The simulation results show that the problem of excess summer temperatures occurring under current climatic conditions in typical, new residential buildings in Germany can be controlled by appropriately adapting the building design and by using solar shading devices. Especially night ventilation can be a very efficient and effective measure to minimize the risk of overheating, irrespective of the type of construction, the use of solar shading systems, the standard of thermal insulation or the building design, thus making the use of an active cooling system superfluous. Even for a worst-case scenario, night ventilation can guarantee comfortable indoor temperatures to a large extent.

KEYWORDS

Ventilative cooling, night ventilation, summer overheating risk, summer heat protection, thermal building simulation,

1 INTRODUCTION

New-built high energy efficient buildings in Germany with highly insulated building components and almost completely airtight building shells raise several new challenges with regard to design, construction and use of these buildings. Cooling, in particular, is an issue that gains importance also in the residential sector, in connection with rising temperatures induced by the climate change.
Alternatively to active cooling, there are also passive and hybrid measures, which minimize the demand of a building for cooling without using mechanical devices. These measures can be grouped in two categories with regard to their impact: (1) passive measures designed to reduce heat gains, (2) measures for activating and discharging structural components that act

as a thermal storage in a building. For instance, measures that contribute to reducing the heat gains include solar shading devices, daylight concepts, energy-efficient appliances or the facade design (bright-coloured paint or planting vegetation). Regarding the thermal activation of building components, the construction of the building plays an important role, and also technical components like phase change materials. The thermal storage is discharged either via hydronic systems (e.g. capillary tube mats) or by means of natural or hybrid ventilation. Increased night ventilation is a particularly cost-effective option to influence the indoor climate such that comfortable conditions are durably ensured, keeping technical expenditure within reasonable bounds. Though the functional principle of night ventilation is well known and its applications are manifold, but it is not widely considered by building planners. One of the reasons for lacking attention might be that the potentials of night ventilation with regard to building cooling cannot be sufficiently estimated. The present study investigates the impact of night ventilation on the indoor climate of typical new residential buildings in Germany.

2 METHODOLOGY

In the scope of the study, two typical, newly constructed residential buildings - a single-family home and a multi-family building - are examined with regard to their overall building energy performance and thermal comfort in summer. The energy performance of the buildings is assessed in accordance with the monthly balance method specified in DIN V 18599 [1] with the Fraunhofer software IBP:18599. To evaluate the summer indoor climate, a thermal building simulation is carried out using TRNSYS 17 [2], with a one-hour calculation time step, applying “Multi-Zone Building Type 56“. The simulation model parameters were chosen in conformity to DIN V 18599 default values. In addition, a verification of compliance with summer heat protection requirements according to German standard DIN 4108-2 [3] is done for the critical rooms.
In the scope of a parameter study, several influences on the indoor thermal comfort of both example buildings will be examined, including the impact of different types of construction, various designs, thermal insulation standards, ventilation strategies and the use of solar shading devices in combination with or without night ventilation. In addition, the effects of storage discharge through night ventilation will be illustrated using thermal building simulation.

2.1 Building models

Figure 1: 3D model of the single-family home

The calculation model for the single-family home is based on typical offers of prefabricated house manufacturer in Germany. It consists of 3 stories including basement, ground floor and top floor. The basement is located entirely below the terrain level; it is partially heated. The

top floor is located beneath a sloped roof with a 45° inclination. The top floor is situated below an unfinished attic. The gable of the pitched roof has an east-west-orientation; the entrance door is placed at the northern facade.
The ground floor includes entrance area, guest room and store room with medium-sized window openings at the northern façade. Living dining room combo and kitchen with large window openings are situated at the south facade. The top floor contains two large bedrooms in the southern part of the sloped roof, and bathroom, smaller bedroom and storeroom in the northern. At each gable side there are two full-height windows, as well as 5 roof windows placed in each room.

Table 1: Building characteristics of the single-family homes

Gross floor [m²]	**Net volume [m³]**	**A/V-ratio [m²/m³]**	**Building envelope [m²]**	**Window [m²]**
271	601	0.64	506	38

A new construction built within the scope of the German research initiative ˈEnEff:Stadt‘ at Lilienstrasse in Munich [4] was selected to serve as the building model for the multi-family building. It consists of 15 residential units on 5 levels, with an average size of 70 m². The upper structure of the building is marked by a slightly inclined roof structure with an inclination of 10°, the bottom of the building is formed by an unheated basement. Contrary to the real building situation, a detached building is being modelled and the balconies at the south facade are not taken into consideration, in order to eliminate the impacts of fixed shading structures.

Figure 2: Southern view of the multi-family building [4]

The floor plan of each story comprises three flats of different sizes, which can be reached via external access balconies and stair cases. In the western part of the building there is a 2-room flat with 55 m² living area (Flat 1). Kitchen, entrance and bathroom of flat 1 are facing to north, while living room and bedroom are facing south with full-height windows. In the center part of the story another 2-room flat with a floor area of 48 m² is located (Flat 2). Entrance and bedroom of flat 2 are on the northern façade, living room and kitchen with full-height windows are facing south. In the eastern part of the building is a 4-room apartment of 105 m² (Flat 3). Entrance, bathroom, kitchen and one bedroom of flat 3 are north facing, while two bedrooms and living room with large window areas are located on the southern façade.

Table 2: Building characteristics of the multi-family building

Gross floor [m²]	**Net volume [m³]**	**A/V-ratio [m²/m³]**	**Building envelope [m²]**	**Window [m²]**
1544	2920	0.43	1554	173

2.2 Energy concept

To carry out further investigations, three energy concepts are assumed for different standards of thermal insulation. The reference case is a building concept according to the minimum requirements specified in the EnEV; in addition, one concept for a 'KfW Efficiency House 55' (KfW 55) and one for a 'KfW Efficiency House 40' (KfW 40) are developed. The KfW Efficiency House levels are defined by the Development Loan Corporation. They are used in the loan programs for energy efficient new building and retrofitting. The number indicates how much energy an efficiency house still needs compared to the minimum standard. The heating system consists of a centralized electrical air-to-water heat pump which is used for space heating and DHW. While the concept of the multi-family building implies a mechanical ventilation system with heat recovery, the single-family house is naturally ventilated. Quality of the thermal insulation varies according to the targeted performance standard.

Table 3: Characteristics of building elements featuring different energy performance standards

		EnEV 2016	**KfW 55**	**KfW40**
U_{Wall}	[W/m²K]	0.28	0.16	0.14
U_{Roof}	[W/m²K]	0.20	0.14	0.10
U_{Floor}	[W/m²K]	0.35	0.25	0.20
U_{Win}	[W/m²K]	1.30	0.95	0.80
$\Delta U_{Thermal\ bridges}$	[W/m²K]	0.05	0.03	0.02
Air tightness n_{50}	[h^{-1}]	1.50	1.00	0.60

In addition to different levels of insulation, it is also examined in which way different types of construction influence the potential of night ventilation. The reference case is a solid construction with reinforced concrete floors/ceilings and masonry internal and external walls. The alternative type of construction provides a timber-post structure with suspended reinforced-concrete floors/ceilings and plasterboard walls as internal walls. A further parameter to be investigated is the influence of the window/facade ratio. Investigations will focus on an increase of the window area by 15% compared to the reference case.

2.3 User profiles

Internal loads

Assumptions for the internal heat loads induced by persons, lighting and electrical equipment are made according to DIN V 18599-10. To create daily profiles, the heat load is divided into hourly values as a function of space usage and time of day, according to the procedure specified in DIN EN ISO 13791 [5].
According to DIN V 18599-10, the net energy need for DHW is assumed to be $q_{w,b}$=11 kWh/m²a in the single-family home and 15 kWh/m²a in the multi-family building. For reasons of simplicity, it is assumed that the DHW demand does not change in time.
The above described approach is not equivalent to the boundary conditions of DIN 4108-2 for verifying summer heat protection on basis of a thermal building simulation.

Solar shading

In both residential buildings, external roller shutters are used as flexible solar shading devices. Fixed shading devices provided by structural measures or the environment are not taken into consideration. In the study three different control strategies for solar shading are examined:

- Automatic control using solar sensors(total radiation on façade)
- Manual control during absence (time control with weather forecast)
- Manual control during presence (internal temperature)

2.4 Other boundary conditions

For the thermal building simulation, the reference climate for Germany at reference location Potsdam (region 4) is used. The solar radiation on facades and roof is calculated based on the isotropic sky model.
The soil temperature of the ground is represented using Type 501 of the TESS library [6]. The mean surface temperature of the soil is assumed to correspond to the average annual external temperature ($T_{e,mean} = 9.5°C$).
The surrounding of the buildings is assumed to be a dispersed, suburban development. For reasons of simplicity, the infiltration air change is assumed to be constant.

2.5 Night ventilation

Increased night ventilation to achieve passive cooling of the building occurs by natural ventilation, no additional fans are used. All openable windows serve as ventilation openings. Depending on the accessibility from the outside (protection against burglary) and the use of the rooms (darkening the bedrooms), different effective ventilation cross-sections are estimated. The calculations are based on the following assumptions:

- Bedroom window: window tilted, shutters closed
- Window accessible from the outside: window tilted
- Other windows: windows half open

The night ventilation is modelled user-controlled and time-dependent, based on the external and internal temperature. If the internal temperature exceeds 24 °C while the external temperature is below 22°C, the windows are opened in the period between 11 p.m. and 6 a.m. The windows remain open until the internal temperature falls below 18°C or precipitation occurs.
The effects of natural night ventilation are modelled using the air mass flows balance method. This means that the air mass flow rate, which is conveyed into a zone, will leave the zone in the same time step, thus preventing the occurrence of low-pressure or overpressure.
The air mass flows, which enter the individual rooms through the window openings in each time step, are calculated following Annex 1 of DIN EN ISO 13791. Both, wind and thermal buoyancy induced by a temperature gradient between the interior and the exterior are considered as driving forces.

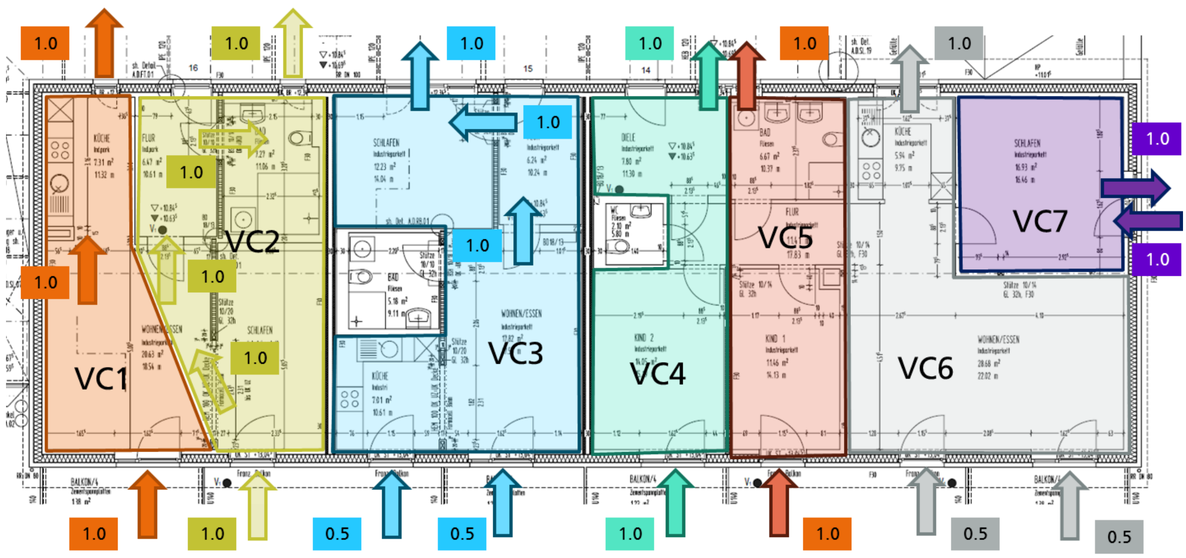

Figure 3: Air flow model for the multi-family building with wind as the driving force

3 RESULTS

3.1 Summer heat protection

The most critical rooms in the single-family home are the three bedrooms on top floor and the living room on ground floor. In the multi-family building, the critical rooms are the bedroom in flat1, living room and kitchen in flat 2 and one of the bedrooms in flat3. All these rooms are characterized by high window/façade ratios per unit floor area (f_{og}) in combination with either south facing windows or roof windows.

As shown in Table 4, in some rooms sufficient summer heat protection can only be verified in conjunction with increased night ventilation of $n = 2h^{-1}$, although the thermal storage mass of the buildings was assumed to be high. If a lightweight construction is used, all other rooms would also tend to overheating.

Table 4: Verification of summer heat protection in critical rooms

	Room	Orientation	f_{og}	Construction	Night ventilation
Single Family Home	Bedroom 1	South	0.23	Medium-weight	-
	Bedroom 2	North	0.32	Medium-weight	2.0
	Bedroom 3	South	0.23	Medium-weight	-
	Living room	South	0.40	Heavyweight	2.0
Multi Family building	Bedroom (flat 1)	South	0.25	Heavyweight	-
	Living room (flat 2)	South	0.36	Heavyweight	-
	Kitchen (flat 2)	South	0.20	Heavyweight	2.0
	Bedroom (flat 3)	South	0.25	Heavyweight	-

3.2 Thermal simulation of buildings

The effects of increased night ventilation on the cooling energy demand of buildings are examined by performing thermal building simulations. The single-family home was completely modelled, including basement rooms and attic floor. In the case of the multi-family building, only the top floor was modelled, for which the highest solar gains were expected due to its location. For reasons of simplicity it was assumed that an air exchange taking place between individual rooms will only be examined for the case of night ventilation.

The reference case was defined for a building featuring the EnEV standard of thermal insulation, built as a heavyweight construction with normal window sizes and provided with automatically controlled solar shading devices. This reference case equates to the building concept, which was evaluated in chapter 3.1.

The overheating risk is examined using eight variants of the building models (see Table 5). The variants are distinguished in terms of insulation standard, type of building construction, control of the solar shading device and window size.

Table 5: Examined variants with regard to their potential of enhanced night ventilation

Case	Name	Insulation	Construction	Window size	Shading control
Ref	Reference	EnEV	Heavyweight	Normal	Automatic
UCS	User-controlled shading	EnEV	Heavyweight	Normal	User-controlled
TCS	Time-controlled shading	EnEV	Heavyweight	Normal	Time-controlled
NoS	No solar shading	EnEV	Heavyweight	Normal	No shading
KfW55	KfW55	KfW 55	Heavyweight	Normal	Automatic
KfW40	KfW40	KfW 40	Heavyweight	Normal	Automatic
LWB	Lightweight building	EnEV	Lightweight	Normal	Automatic
IWA	Increased window area	EnEV	Heavyweight	Increased	Automatic

Overheating risk without night ventilation

The results of the thermal building simulation suggest that the single-family home in the reference case (Ref) is not prone to overheating in summer. As illustrated in Figure 4, the threshold value for excess temperature degree hours acc. to DIN 4108-2 of a maximum of 1200 Kh is not exceeded. The excess temperature degree hours are calculated from the difference between the hourly operative temperature and the reference value for the summer climate region B of 26°C, cumulated across all hours with excess temperature.
Modifications in the control of the solar shading devices (user-controlled (UCS) or time-controlled (TCS)) do not create a risk of overheating. It would, however, make a difference if all solar shading devices were deactivated (NoS). When examining the impacts of the energy concept (KfW55 and KfW 40), excess temperature degree hours are found to increase along with enhanced thermal protection, while remaining clearly below the threshold values. This result meets the expectation that additional insulation even has a rather positive effect on summer heat protection, improved leakage characteristics of the building envelope however prevent the discharge of heat loads by way of infiltration air flows.
The reduced heat storage capacity of a lightweight construction (LWB) results in a significant increase of excess temperature degree hours; however, the values for all rooms of the single-family home remain clearly below the admissible threshold values. The variant with extended window areas (IWA) is not associated with any significant increases in excess temperature degree hours. From this, it can be concluded that the choice of appropriate solar shading devices is of greatest importance for the single-family home.

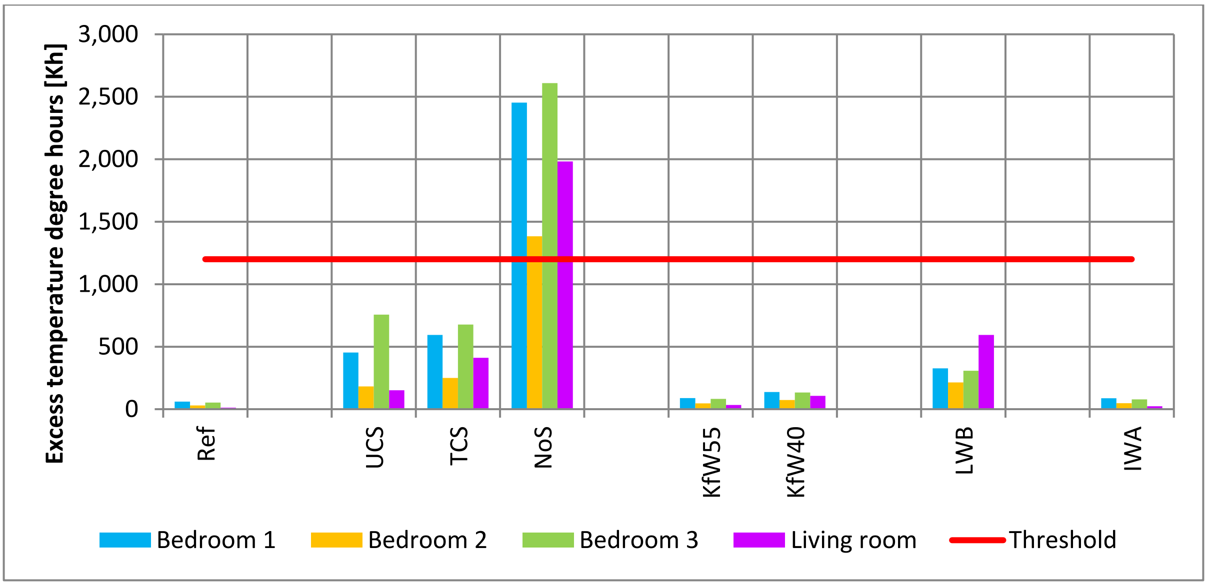

Figure 4: Impact of solar shading, thermal protection, heat storage capacity and size of windows on the excess temperature degree hours in the critical rooms of the single-family home. (Ref = Reference case, UCS = User-controlled shading, TCS = Time-controlled shading, NoS = No Solar shading, KfW55 = KfW Efficiency House 55, KfW40 = KfW Efficiency House 40, LWB = Lightweight building, IWA = increased window area).

Likewise, the reference construction of the multi-family building (Ref) does not tend to overheating as the results of thermal building simulation suggest (see Figure 5). The only critical room featuring a value only just below the maximum admissible excess temperature degree hours is the kitchen of interior flat 2.
A variation of the automatic solar shading control in the reference case would lead to an increase of the overheating risk. The least influence is found for the user-controlled operation (UCS). In the case of time-controlled operation (TCS), the threshold values would exceed in

the living room and kitchen of flat 2. If solar shading is entirely dispensed, excess temperature degree hours will exceed 1200 Kh in all rooms. If the level of thermal insulation is further enhanced, the excess temperature degree hours in the living room and kitchen of flat 2 would exceed the threshold value, while the other rooms would not be affected. Enlarging the window areas (IWA) causes exceedance of the threshold values only in the kitchen of flat 2, in a lightweight construction (LWB) also the living room of flat 2 would exceed the threshold.

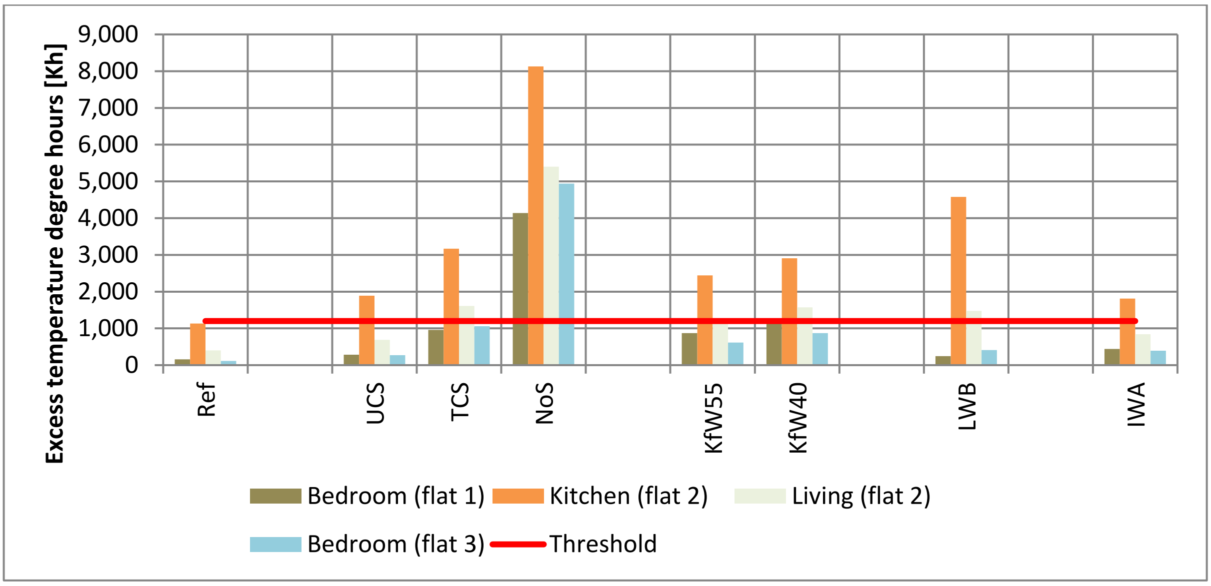

Figure 5: Impact of solar shading, thermal protection, heat storage capacity and size of windows on the excess temperature degree hours in the critical rooms of the multi-family building. (Ref = Reference case, UCS = User-controlled shading, TCS = Time-controlled shading, NoS = No Solar shading, KfW55 = KfW Efficiency House 55, KfW40 = KfW Efficiency House 40, LWB = Lightweight building, IWA = increased window area).

Effects of night ventilation

Targeted discharge of heat via extended ventilation through windows during night-time hours can substantially reduce daytime indoor temperatures. Figure 6 presents the thermal building simulation results of the living room in the single-family home on the night of 20 to 21 July.
In the evening hours before night ventilation sets in, the indoor air temperature (red line) remains relatively constant above 24°C. The outdoor air temperature (bright blue) drops from 30°C at 8 p.m. to 18°C at 5 a.m. After sunrise, it rises above 20°C. Night ventilation starts as soon as the outdoor temperature falls below the indoor air temperature. Night ventilation remains active until the windows are closed at 7 a.m. in the morning. In the first hour, the force driving the air exchange is the wind acting on the east façade (green column). In the next two hours, the temperature difference between indoor air and outdoor air is the driving force (blue). After four hours the wind velocity augments notably and the wind on the south facade becomes the driving force (orange). In the sixth hour, the wind changes to an eastern direction; hence, the wind on the east facade becomes the driving force.
As expected, the indoor temperature continually declines after night ventilation has begun. In the morning hours, when the wind on the east facade passes through the kitchen into the living room, the indoor temperature rises again until it recovers 23°C at 8 a.m.
At first sight, this course may be somewhat surprising, because the indoor temperature rises at a point in time when the outdoor temperature is still below the indoor temperature and solar gains are not yet expected. The reason for this development becomes evident by looking on the surface temperatures of the enclosing building components (floor, ceiling, and external wall facing south). Due to higher heat storage capacity of building components compared to

that of air, the indoor air is reheated, if the air volume flow passes into the living room is no longer sufficient to discharge the heat dissipated by the building components.

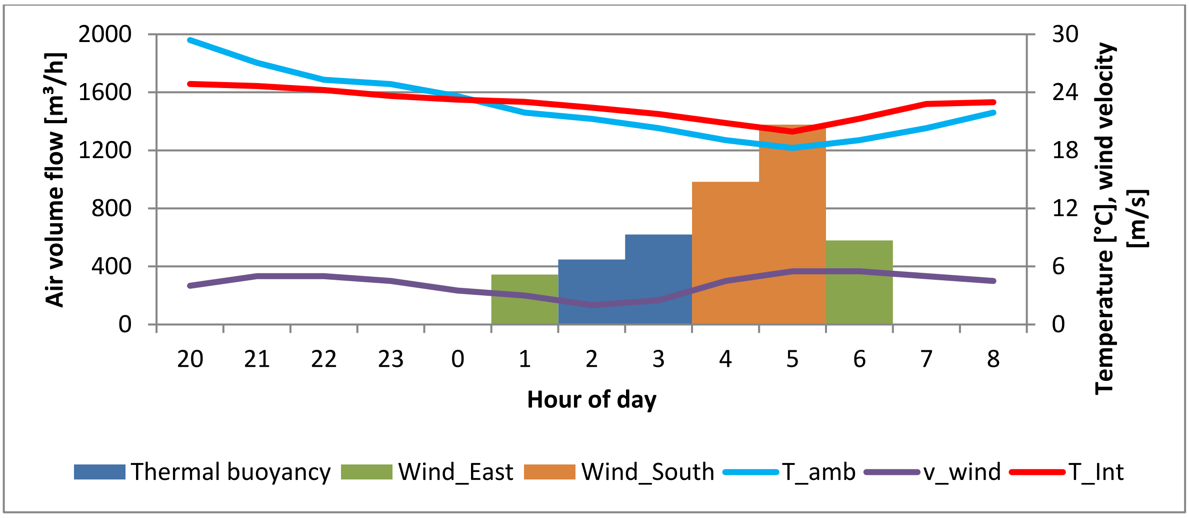

Figure 6: Air volume flow of night ventilation in the living room of the single-family home on 20 July. (T_{amb} = Outside temperature, T_{int} = Inside temperature v_{wind} = wind velocity)

As the parametric study has shown, there are several variants, which could lead to problems associated with excess temperatures. Particularly in lightweight constructions and the variants without solar shading, a considerable amount of excess temperature degree hours was stated. As shown in Figure 7, these excess temperature problems can be almost entirely eliminated in both cases, by using night ventilation. Only in the kitchen of flat 2 and in the bedroom of flat 3, the simulation results still show minor excess temperature degree hours.

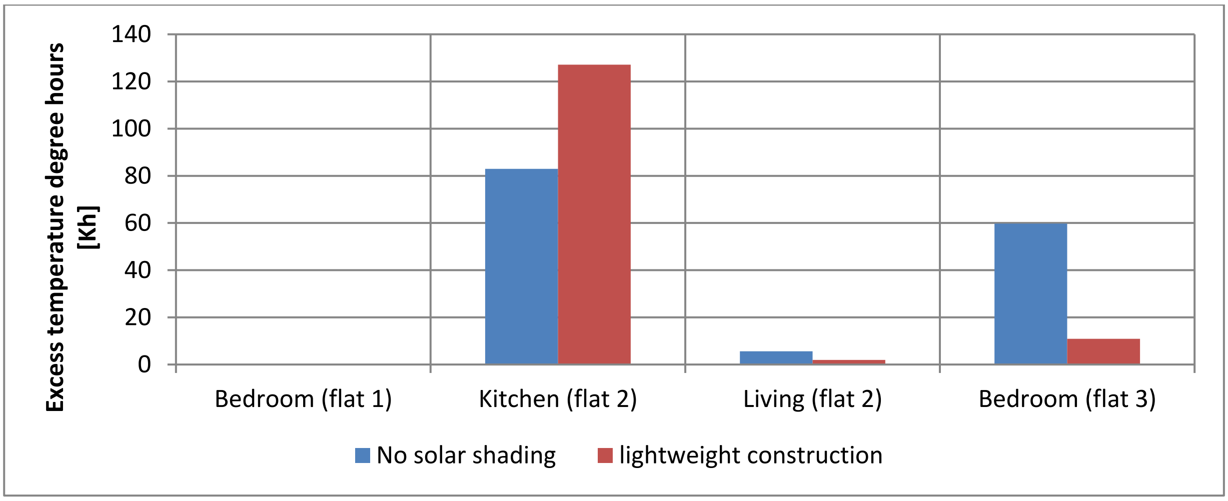

Figure 7: Influence of night ventilation on the excess temperature degree hours in the rooms of the multi-family building for the variant without solar protection.

In a second step, the critical variants with regard to summer overheating were combined. It was examined whether night ventilation suffices to reduce overheating in a combination of 'KfW Efficiency House 40', lightweight construction and no solar shading devices. The simulation results have shown that night ventilation is not quite sufficient to respect the threshold values in all rooms in this absolutely extreme scenario. In the living room and in the bedrooms the threshold value would be exceeded. However, if the lightweight construction is replaced by a solid construction, night ventilation can even compensate a combination of unfavorable parameters.

4 CONCLUSIONS

The case study has demonstrated that the problem of excess summer temperatures occurring under current climatic conditions in typical, new residential buildings in Germany can be controlled by appropriately adapting the building design and by using solar shading devices.

In the scope of the present case study, making intelligent use of solar shading systems was identified as the most critical parameter for ensuring thermally comfortable indoor environments in summer. The second influential parameter that was determined is the heat storage capacity of the structural components of the building. The level of thermal insulation was however found to be of minor importance.

The thermal simulation has shown that overheating problems are likely to occur particularly in the multi-family building (namely, due to the higher area-specific internal heat loads).

Here, night ventilation can be a very efficient and effective measure to minimize the risk of overheating, irrespective of the type of construction, the use of solar shading systems, the standard of thermal insulation or the building design. Even for a worst-case scenario combining the least favourable parameters, night ventilation can guarantee comfortable indoor temperatures to a large extent.

Beyond the scope of the present study, future research work will have to deal with further issues. These include investigations of alternative control strategies for night ventilation, such as automated ventilation opening or motor-driven tilting mechanisms. The question which potentials night ventilation holds in other climatic zones receiving higher amounts of global radiation is also left unresolved. Furthermore, an analysis of the effects of a rise in temperature due to global warming could also be an interesting research point.

5 ACKNOWLEDGEMENTS

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