Energy efficient office buildings with passive cooling – Results and experiences from a research and demonstration programme in Germany

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ABSTRACT

To gain access to the energy use in office buildings, the German Federal Ministry for Economy 1995 launched an intensive research and demonstration programme. In advance of the 2002 EU energy performance directive a limited primary energy coefficient of about 100 $kWhm^{-2}a^{-1}$ as a goal for the complete building services technology was postulated (HVAC + lighting). Further condition was that active cooling be avoided. Techniques like natural or mechanical night ventilation or heat removal by slap cooling with vertical ground pipes were applied as well as earth-to-air heat exchangers in the ventilation system. An accompanying research was established to keep track of the results and lessons learned from about 22 demonstration buildings realized and monitored until end of 2004. As one outcome this paper summarizes the energy performance of a selection of characteristic buildings together with an overview on the summer thermal comfort situations achieved.

1. INTRODUCTION

1.1 Energy use in office buildings

Numerous office buildings of the eighties were designed to isolate the internal conditions from the outdoor climate as completely as possible, at the cost of high energy consumption. Thermal and visual comfort as well as the air quality is guaranteed by extensive technical building services for heating, ventilation, air-conditioning and lighting (HVACL). High investment and running costs are accepted to ensure that it can control even extreme indoor conditions caused by generously glazed building envelopes. In combination with the space demand of wiring for communications technology of that time - double floors, suspended ceilings - it is quite common for technical services to occupy 20 to 30 % of the building volume. The main share of the electricity consumption is due to the HVACL facilities, not the office equipment.

Despite the heat generation associated with electricity consumption within the building (internal heat gains), the space heating demand in Mid and North European Climate is still high due to the high proportion of glazing and the high air exchange rates. Figure 1a gives a qualitative impression of a typical energy consumption profile as a function of the outdoor temperature. In addition to a base energy load, which is independent of the weather, there is a contribution for heating and humidifying below the balance temperature, and for cooling and dehumidifying above it. The base load is caused by office equipment and the idling consumption of building services technology. The waste heat associated with the base load affects the position of the balance temperature. The higher the base load, the lower is the balance temperature. Due to the decoupling of the room air from the building mass - suspended ceilings, double floors, lightweight walls - and the maintenance of constant indoor conditions throughout the whole year, there are hardly any days when there is neither active heating nor cooling.

1.2 Thermal Comfort and Health

The diverse technical approaches to achieve a

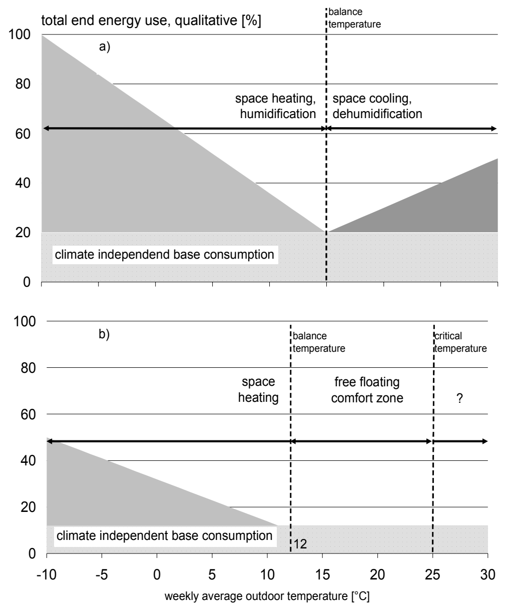


Figure 1: Qualitative profile of the energy consumption of a "conventional building" (a) compared to a "lean building" (b).

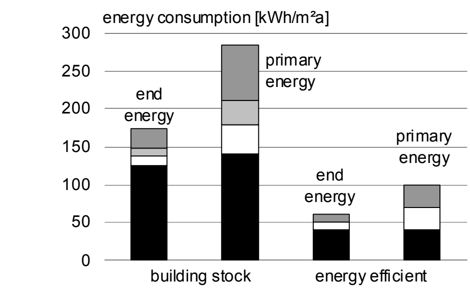
good indoor climate were often accompanied by complaints from office workers about many types of discomfort and dissatisfaction, which are summarised as the "Sick Building Syndrome". One German investigation of this phenomenon, the so-called "ProKlima-Projekt", reaches the conclusion that although buildings with air conditioning maintain an objectively good indoor climate, they are subjectively rated lower than naturally ventilated working conditions by the majority of persons questioned. The rating is significantly affected by the degree to which an individual can determine the conditions prevailing at his workplace (Bischoff et al., 2003).

Today an increasing fraction of office buildings are being constructed or retrofitted which allow individuals to control their own indoor climate to a large extent, and which replace almost complete isolation from the weather outdoors by a moderate interaction. Daylit workplaces and the option for natural ventilation are typical characteristics. However, a combination of integrated measures to achieve so-called "passive cooling" is a pre-requisite if summer comfort is to be ensured without actively cooling or dehumidifying the inlet air. This type of concept became known as "lean building", due to the smaller volume of the service equipment required. The task is to design buildings such that even when the weather outdoors varies greatly, the indoor conditions remain within a well-defined comfort *zone*, which meets the expectations of the occupants (Fig. 1b). The indoor air conditions will vary more than in a completely air-conditioned building. Research on thermal comfort has shown that this does not have to affect the perceived comfort negatively (E & B 2002). New building codes in some countries start to take this into account by adapting the maximum acceptable indoor temperature to the monthly mean (USA, de Dear and Brager, 2002) or slighting mean outdoor temperature (The Netherlands, Boerstra et al., 2003), instead to the current outdoor temperature (Germany, DIN 1946, part 2).

2. RESULTS AND EXPERIENCES

2.1 Energy Monitoring

Table A1 in the appendix gives an overview of the projects monitored. Detailed information together with a comprehensive overview on results and experiences are presented in (Voss, 2005). Figure 3 summarises the results from



	building stock		energy efficient	
lighting	25	75	10	30
cooling	11	30	0	0
ventilation	13	40	10	30
heating	125	140	40	40

Figure 2: Target values for energy efficient office buildings according to the programme compared to consumption values for office buildings from the existing stock in Mid European climate according to (Weber 2002). The net heated floor area is used as the reference area. End energy was transferred to primary energy by a factor of 3 in the case of electricity and about 1 for all other forms of end energy.

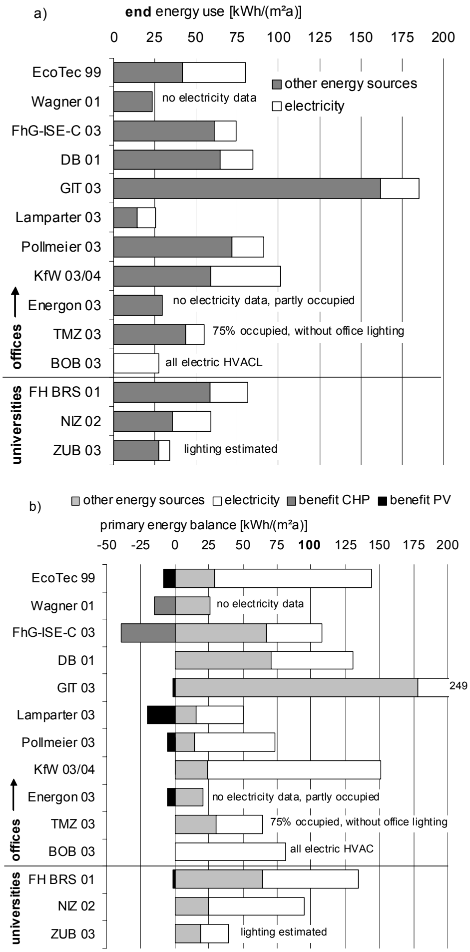


Figure 3: Measured end energy (a) and primary energy coefficients derived from them (b). The primary energy factors and electricity credits are based on German DIN 4701/10: Electricity 3, fossil fuels 1.1, biomass 0.2. To simplify the balancing procedure, photovoltaic electricity (PV) was evaluated with the same electricity credit as for combined heat and power plants (CHP). The consumption values refer to HVACL. The numbers following the project titles indicate the year for the measurements. The data source in each case was the university, which was responsible for the measurement programme. In the case of the "FhG-ISE" building, a zone of 525 m^2 consisting purely of offices plus the adjoining access areas was selected from the Institute building with a total area of 14,000 m^2.

buildings for which data from at least one year were available. We have chosen to present the information as a graph rather than numerically, as the boundary from HVACL to user-specific electricity consumption (PC, printers etc.) was difficult to define in some cases. This could cause quantitative but not qualitative changes to the results. Particularly for separating the electricity use for the type of energy service requires a very detailed and expensive metering concept. It is not common to allocate the electric circuits within a building according to the equipment connected to them. In many cases, detailed analysis of the electricity consumption helped to identify weaknesses in system operation and aid their correction.

Nine of the fourteen buildings presented show a primary energy consumption below or close to the agreed limit of 100 kWh m^{-2}a^{-1}, fife lie above the limit. It is satisfying to see that the consumption for all of the buildings is much lower than the comparative values for the building stock according to Figure 2. The limit was exceeded because of unexpectedly high heating demands (DB, GIT) a high electricity consumption for lighting (FH BRS), etc. Some of the causes are due to the building concepts, others could have been avoided by an improved energy management. The Pollmeier building avoided high consumption values for primary energy, despite unexpectedly high heating energy consumption by burning wood offcuts from its own sawmill, representing a largely CO_2-neutral source. Combined heat and power plants result in a primary energy credit (Wagner, ISE), as the measured gas consumption also contributes to electricity generation and thus to substitution of grid electricity. Drawing heat from a district heating network with CHP also proved to be favourable (ECOTEC, ZUB).

2.2 Passive Cooling

In order to improve indoor conditions in summer, so-called "passive cooling" concepts were integrated part of each building design in different ways and to a varying extent. Passive cooling means the interaction of all measures which act to reduce the heat gains on the one hand, and on the other, which make natural heat sinks - night air, ground - accessible. The remaining heat loads are transferred to the surroundings with a certain time delay. Heat storage in the building construction, both during the course of a day and over longer hot periods, is substantial, (Fig. 4) (Pfafferott, 2004).

In view of the limited cooling capacity and

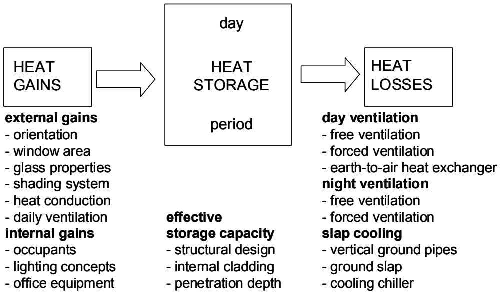


Figure 4: The principle of passive cooling and main parameters influencing the building energy balance.

the long time constants, the main design priority is to restrict the amplitude and dynamics of *external heat gains*. For this reason, none of the buildings includes a fully glazed facade. The average ratio of glazing to façade area was 43 % or 27 % referring to the floor area respectively. Almost all of the buildings use external sunshading devices with the only exceptions in the case of buildings with slap cooling systems (enhanced cooling capacity). Experience indicates that the total solar energy transmittance (g value) for the glazing and sun-shading should not exceed 15 %. This can be achieved for internal blinds or blinds in the gap between the glass panes only in combination with solar-control glazing (g<40 %). Nearly all sunshading systems are motorised, so that they can be activated before working hours begin, and can be closed to cut solar gains at weekends. It has been observed in many cases that blinds are not closed manually until the office workers are disturbed by glare at their desks. Venetian blinds were seldom closed completely but operated in the so called “cut-off” mode. In both cases this means that the potential for improving the indoor conditions with effective sun-shading is far from being realised. A view of the surroundings is clearly particularly significant for a pleasant working environment. Taking this into consideration, g-values should be assumes less optimistic during planning and additional passive solar-control measures take on new significance.

Average daily total *internal heat gains* observed range between 100 and 200 Wh/m². The range refers to the density of occupation, the operation mode of the computer systems and the lighting concepts (Table 1).

The *building structure* has the task of modu-

Table 1: Internal heat gains detected in selected projects. Numbers refer to Wh per m² office floor area and day. Data source: Monitoring teams according to Tab. A1.

	total	persons	equipment	lighting
Wagner	100	24	66	10
DB Netz	141	30	79	32
Lamparter	100	40	-	-
FhG ISE	188	53	125	10
Pollmeier	92	21	50	21

lating heat acceptance and heat release over short (hours) and longer periods (days). If the heat transfer from indoor air to the structure is hindered, e.g. by a suspended ceiling, the short-term storage capacity is drastically reduced. All of the buildings investigated have steel-reinforced concrete ceilings without additional suspended ceilings. If the room usage demanded further acoustic measures, thermally open constructions, absorbers suspended under only part of the ceiling or wall-mounted absorbers were used.

Most of the projects from the beginning of the programme applied night ventilation in combination with earth-to-air heat exchangers to *remove excess heat* in summer, several of the more recent projects have applied slab cooling in connection with vertical ground pipes or ground pillars due to the increased cooling capacity, refer Table A1. The amount of heat removed from the building structure by night ventilation depends mainly on:

- the air flow rate,
- the temperature difference (T_{in}–T_{out}),
- the time and duration of ventilation,
- the ventilation efficiency.

Table A1 indicates that both the mechanical ventilation systems as well as free convection are applied for night ventilation. Advantage of mechanical ventilation is that the air flows can be controlled better; the disadvantage is the electricity consumption. The consumption can be justified if there are large temperature differences and the air-flow path minimises pressure losses (specific electricity demand ≤ 0.2 W per m^3h^{-1} air flow). As the air-exchange rates increase, the coefficient of performance decreases, as the ventilation efficiency does not increase to the same extent as the electricity consumption.

As part of the accompanying research standardised graphs were proposed to allow results on the indoor conditions in summer to be compared between the different projects. Figure 5 illustrates the results using annual cumulative frequency distributions for the temperature. If the upper limit of 25 °C according to DIN 1946, Part 2 is taken as a reference, the buildings demonstrate that the frequency of higher temperatures can be kept low with suitable passive cooling measures. On the basis of the analyses made to date, it appears that exceeding this upper limit for at most 10 % of the usual working hours is just tolerable for high user acceptance; the planning goal should be 5 %. This upper limit should be observed for each room individually resulting in very high demands on the passive cooling for corner rooms with glazing in two or more walls. Building simulations done for planning purposes must consider rooms of this type as separate zones; a simplified approach which combines them with other zones in the building will lead to unrealistic results

3 OUTLOOKS

Passive cooling does *not guarantee* thermal comfort, but dramatically *improves* the overall situation in free running indoor environments. Drawback is the limited control for the individual, local performance. The wording “cooling”

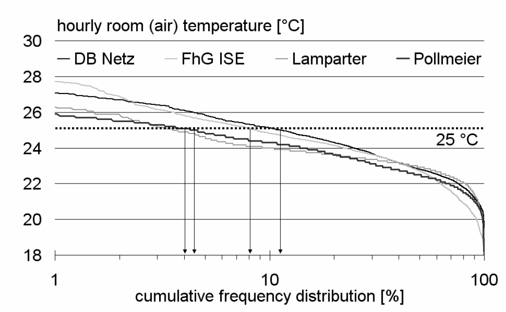


Figure 5: Cumulative frequency distributions for the hourly average temperatures in the offices of four selected buildings. The temperature limit of 25°C according to DIN 1946-2 is exceeded for 4 % (Lamparter), 4.5 % (Pollmeier), 8 % (FhG-ISE) and 10.5 % (DB) and of the working hours during the course of one year. Due to the type and position of the temperature sensors, the values quoted for Lamparter are air temperatures, whereas the values for the other projects approximately represent the operative temperature. The meteorological boundary conditions differ between the buildings due to their different locations (e.g. maximum outdoor temperature FhG-ISE: 37 °C, Lamparter: 36 °C, DB: 34 °C, Pollmeier: 35 °C).

promises a not fulfilled property from the user - non expert - point of view. Thus it is important to communicate the real service capability properly.

Due to the complex interactions between the weather, the building, the technical services and user behaviour, the success of a passive cooling concept is jeopardised at many points of the planning and implementation process. There is no chiller available as a back-up. Thus, any errors in planning or implementation directly affect the indoor working conditions for the worse. Due to the major economic significance of high-quality working conditions, the *planning certainty and quality assurance* must be further improved. Ongoing research of the authors aims towards this direction.

Furthermore, the concepts must become more robust. To achieve this, more knowledge must be gained on typical *user behaviour patterns* concerning ventilation through windows, operation of blinds and manually activated components of passive cooling (ventilation flaps, etc.). Initial analyses have been carried out (Pafferott 2005). Simulation models can then use statistically reliable user models.

The positive results from the new buildings justify the wider implementation of passive cooling in office building retrofit. In applications without sufficient thermal mass, building structure integrated phase change materials (PCM) show promising results in pilot applications.

In contrast to an air-conditioning system, which is designed to maintain essentially constant indoor conditions throughout the year, the passive cooling approach only modulates between the conditions indoors and outdoors. As a result, the indoor conditions vary over a larger range. Targets for thermal comfort in this type of building should take this into account. This demands fundamental research on thermal comfort and consequences for building standards.

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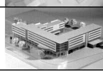
APPENDIX

Table A1

		passive cooling concept		
buildings		eta hx*	night ventilation	slap cooling
ECOTEC			active	
Wagner		•	passive	
FhG ISE		•	hybrid	
DB Netz		•	hybrid	
FH BRS		•	passive	
GIT		•	active	
Lamparter		•	passive	
NIZ			passive	
Surtec		•	passive	
ZUB			hybrid	•
Pollmeier			active	
Solvis			active	
KfW			passive	
Energieforum			passive	•
Energon				•
TZM				•
BOB				•
GMS				•
Lindenberg				•
UBA		•	passive	
SIC			active	•

* eta hx: earth-to-air heat exchanger