Comfort and well-being in solar buildings Results from a European Audit.

Claude-Alain Roulet[1], Chrit Cox[2] and Philo Bluyssen[2]

[1]LESO-PB, École Polytechnique Fédérale de Lausanne, Switzerland

[1] TNO Environment and Geosciences, Delft, the Netherlands

ABSTRACT : Within the European research project HOPE, 97 apartment buildings and 67 office buildings - a large part of which designed to be energy-efficient - were investigated using checklists regarding building characteristics and questionnaires addressed to the occupants regarding their perceived comfort (thermal visual, acoustic and indoor air quality) and well-being (sick building syndrome and allergies). Interpretation of the collected data already showed that, on the average, occupants of low energy buildings feel better and are better satisfied with their indoor environment than occupants of other buildings. This contribution addresses in particular those buildings that have one or more characteristics of passive solar architecture and give statistical comparisons between the well-being as perceived by the occupants of these buildings and of the others. It is found that, among all the buildings audited within the HOPE project, most solar buildings are in the top group for energy performance and are at least as healthy and comfortable as the other ones.

Keywords: energy, buildings, passive solar, comfort, well-being

1 INTRODUCTION

Passive solar design aims to produce energy efficient buildings through adaptation to local climate and situation. Architecture should however not be limited to energy issues, since buildings are inhabited and should therefore also be healthy and comfortable. This is of primary importance, since, in developed countries, human beings spend more than 90% of their time within buildings.

A recent European project audited several buildings in nine European countries, looking at the comfort and well being as perceived by their occupants. Among these audited buildings, some had active solar systems or passive solar characteristics and/or specific devices such as mechanical ventilation with heat recovery aiming to reduce the energy use.

For this paper, the collected data were interpreted to show the differences in occupant's well being between these particular buildings and the other ones.

2 THE HOPE PROJECT

2.1 General description

The HOPE (Health Optimisation Protocol for Energy-efficient Building) European research project aimed to show that it is possible to design low-energy buildings with good indoor environment quality.

This multi-disciplinary study was performed in 160 buildings (96 apartment buildings and 64 office buildings) 75% of which were selected for having energy saving design or devices. This investigation was carried out in nine European countries. Three assessment methods were used [1]:

(a) an inspection of each building according to a checklist, providing data on the building and its environment,

(b) interviews with building management, from which, among others, information on building energy performance was collected, and

(c) questionnaire surveys of occupants, providing information on how they feel and perceive their indoor environment.

2.2 Collected data

The following information was collected:

Buildings characteristics were collected according to a checklist through interviews with the building management and a walk-through survey. The checklist includes, among others:

- Location, situation, year of completion
- Energy saving measures, including passive solar design
- Dimensions, number of storeys, floor area, ceiling height, number of occupants
- Type and quality of thermal insulation
- Building thermal time constant
- Type and location of solar shadings
- Type and size of glazing
- Presence of indoor contaminants such as mould, asbestos, lead paints, control ingress of radon
- Kind of heating and cooling if any
- Ventilation system, operable windows
- Equipment in air handling unit (heating, cooling, humidification, drying, filters, heat recovery, duct material, etc.)

Delivered energy use was assessed from building records where available, and from energy bills in the other buildings. Wherever possible, the data were collected for several years and averaged to assess a mean yearly consumption. The net calorific value was used to quantify the energy from fuels, and this amount was summed to the electricity consumption to get the total annual delivered energy. A rough approximation of primary energy use, in which a weight 2.5 was allocated to electricity, while a unity weight was kept for the other energywares, was also calculated. This method corresponds to the operational energy rating proposed by [2]. As proposed in [3], the Energy Performance Indicator (or EP indicator) is calculated by dividing the total delivered energy use in kWh by the gross conditioned floor area to take account of the building size. This area was either given by the building management or measured on building drawings. Since heating and cooling was not metered separately from the other energy uses in most buildings, no correction was made for climate.

For **perceived comfort,** questions were asked to occupants in a self-administered questionnaire. The basic question was: *How would you describe typical working conditions in the office (or in your flat)?* Then for each item, the occupant was to cross one box, from 1 (which stood in most cases for good or satisfactory) to 7 (which marked an unsatisfactory situation). The same questions were asked for winter and summer seasons. The items and qualifications corresponding to extreme marks are given in Table 1. The results for a building are the average marks of all respondents for each question.

Table 1: Questions related to comfort

	Item	Grade 1	Grade 7
Thermal comfort	Temperature - comfort	Comfortable	Uncomfortable
	Temperature - hot/cold*	Too hot	Too cold
	Temperature - Stability	Stable	Varies during the day
	Air movement*	Too still	Too draughty
Air quality	Air quality - Humidity*	Dry	Humid
	Air quality – Freshness	Fresh	Stuffy
	Air quality - Smells	Odourless	Smelly
	Air quality - Global	Satisfactory	Unsatisfactory
Light	Natural light Glare from sun and sky Artificial light Glare from artificial light Light overall	Satisfactory	Unsatisfactory
Noise	Noise from outside Noise from building systems Other noise from the building Noise overall Vibration in the building	Satisfactory	Unsatisfactory
	Comfort overall	Satisfactory	Unsatisfactory

* Items marked with an asterisk are two-sided: the best mark for them is 4, both 1 and 7 being not satisfactory.

For **perceived health**, the occupants were asked if they had two or more episodes of eight symptoms, and if they felt better on days out of the office. A symptom that disappears when the person is out of the building is assumed to be building-related. The list of symptoms included those commonly connected to the sick building syndrome, i.e., in office buildings: dryness of the eyes, itchy or watery eyes, blocked or stuffy nose, runny nose, dry throat, lethargy or tiredness, headaches, dry, itching or irritated skin. In homes, additional symptoms are sneezing and breathing difficulties. From the obtained replies, a building symptom index (BSI) was calculated as the average number of building-related symptoms per occupant.

Interpretation of some of these data showed that low energy buildings were healthier and more comfortable than the other ones [4, 5], and allowed to propose guidelines for designing buildings that are healthy, comfortable and energy efficient [6].

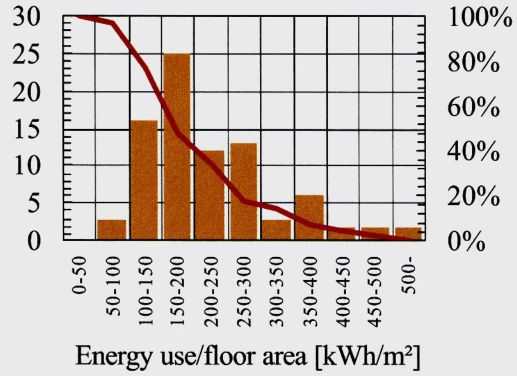
3 ENERGY RELATED TYPOLOGY

3.1 Energy performance indices

75% of the buildings audited within the HOPE project were chosen because they had been designed to have a good energy performance.

Figure 3.1 shows the frequency and cumulated distributions of the energy performance indicators in the audited homes and office buildings. The bars show the number of buildings (left scale) that have their EP indicator within the range shown on the x-axis, while the curve shows the percentage of buildings (right scale) that have an EP indicator larger than the lowest value of the range.

It should be noticed that these distributions are not representative of the European building stock, since the sample is biased by the selection of low energy buildings for 75% of them. The median value for apartment buildings is 140 kWh/m² and 200 kWh/m² for office buildings.



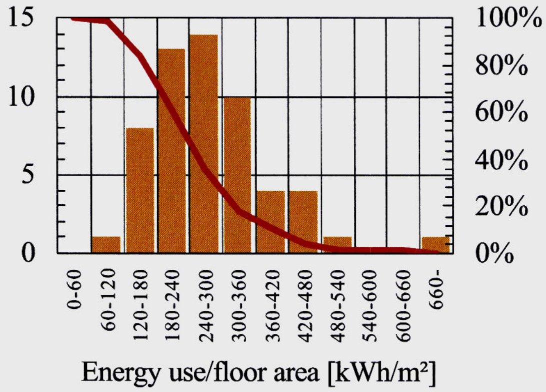


Figure 3.1: Distribution of the energy performance indicators in homes (top) and office buildings (bottom).

Significant differences were found between buildings that use less and more than these median values, which are published elsewhere [4]. The main differences are that low energy buildings are more recent and perceived healthier and more comfortable than the other ones.

3.2 Office buildings

Out of the 64 audited office buildings, 28 have heat recovery in a mechanical ventilation system, and 22 do not. The others are naturally ventilated.

Only three office buildings are characterised by a passive solar design. Two of them are in the Netherlands and one is in Switzerland. They are described in more detail in Section 5.1.

3.3 Residential buildings

Out of the 96 apartment buildings, 53 are ventilated by operable windows, 2 by other natural ventilation systems such as stack ducts, 17 have mechanical ventilation and 22 a hybrid (mechanical and natural) ventilation design. None of them has a cooling system in the air handling unit. Among the mechanically ventilated buildings, 18 have heat recovery.

Thirteen apartment buildings have passive and/or active solar design. Five have only passive solar design, seven only active solar systems and one has both. Three of them are in Switzerland, four in Denmark, three in the Netherlands and three in Portugal.

4 HEAT RECOVERY

Natural ventilation is the passive way of evacuating heat and contaminants and bringing fresh air into buildings. This is not always possible, and mechanical ventilation may be needed in noisy or polluted areas for ventilating large enclosures or for recovering heat.

It is statistically shown that buildings with mechanical ventilation or air conditioning are, on the average, perceived as less healthy or comfortable than buildings with natural ventilation [7]. However, there are healthy mechanically ventilated buildings. We were interested to see if, among mechanically ventilated buildings, there are differences between buildings with and without heat recovery.

4.1 Office buildings

Table 2 shows, for several characteristics, the average values over office buildings with and without heat recovery. The last column indicates the significance of the difference: N/D means not different, N/S means not significant, one star shows an acceptable significance, the probability of getting the difference by pure chance being less than 10%, two stars indicate a good significance, the probability being less than 5 %, and three stars are put when this probability is smaller than 1%.

Table 2: Average characteristics of office buildings with and without heat recovery.

Heat recovery?	Yes	No	Sign.
Number of buildings	28	22	
Year completed	1989	1984	N/S
Number of storeys above ground	5	6	*
Total treated floor area [m²]	15600	9838	**
Typical number of occupants	331	434	N/S
Percentage with cooling in AHU .	75%	64%	N/S
Mean outdoor temperature in winter	5.0	7.2	***
do. in summer	13	13	N/D
Energy performance index [kWh/m²]	184	293	***
Electricity use/floor area [kWh/m²]	112	196	***
Building symptom index BSI	1.85	2.20	*
Comfort overall in summer†	3.38	3.35	N/D
Comfort overall in winter†	3.13	3.16	N/D
Air quality in summer†	3.82	3.82	N/D
Air quality in winter †	3.69	3.60	N/S

†: Scale goes from 1, satisfactory, to 7, unsatisfactory.

Office buildings with heat recovery are, on the average, significantly larger and located in colder winter climates, but they have the same number of occupants and summer average temperature. As expected, their energy performance index is much better, and their electricity use is nearly half that of buildings without heat recovery. This cannot be the result of heat recovery only, but could be the result of energy conscious design that includes, among others, heat recovery systems. The difference for the total energy performance index shall of course not be entirely attributed to the heat recovery.

There is no difference for perceived comfort or air quality, but there is a difference for the BSI or average number of building related symptoms per occupant: the buildings with heat recovery are perceived as healthier.

4.2 Apartment buildings

Table 3 is the same as Table 2, but for apartment buildings. The size and occupancy of both types are similar, as is the outdoor temperature in the heating season. For these buildings, there is no information on temperature during summer. The energy performance index is, as expected, much better in buildings with heat recovery than in the other ones, but the electricity use is the same in both cases, though much lower than that of office buildings.

In one of these buildings, odour problems were found at the beginning, since the rotating heat exchanger also recovered heat from the kitchen hood. Some cooking odours were transferred to supply air by adsorption-desorption on the exchanger wheel surface [8]. This problem was solved by installing active charcoal filters in the supply duct.

Table 3: Average characteristics of apartment buildings with and without heat recovery.

Heat recovery?	Yes	No	Sign.
Number of buildings	18	23	
Year completed .	1988	1980	**
Number of storeys above ground .	5.91	7.44	N/S
Total treated floor area [m2] .	6208	8324	N/S
Typical number occupants .	172	204	N/S
Mean outdoor temperature in winter	4.93	4.72	N/D
Energy performance index [kWh/m²]	139	208	***
Electricity/floor area [kWh/m²] .	29	24	N/S
Building symptom index BSI	1.29	1.12	N/S
Comfort overall in summer†	2.73	2.82	N/S
Comfort overall in winter†	2.51	2.84	**
Air quality in summer†	2.84	3.01	N/S
Air quality in winter†	2.77	2.88	N/S

†: Scale goes from 1, satisfactory, to 7, unsatisfactory.

Differences for BSI, summer comfort and air quality are not significant, but overall comfort in winter is perceived better where heat recovery is installed.

5 SOLAR BUILDINGS

As already said above, the best buildings for energy performance are also the best for perceived health and comfort [4]. We are interested here in the well being of occupants of so-called solar buildings. For this purpose, we sorted the buildings into two groups, those having a passive solar design and/or active solar systems, and the other ones.

Another strategy could be to compare buildings with solar design and other buildings having a good energy performance but no solar design. This has the advantage of comparing buildings with similar energy performance, but the problem in this case is that all buildings have some solar gains through the windows, and we did not collect enough information to clearly separate the buildings with large solar gains from the others.

5.1 Office buildings

Among the audited buildings, there are only three office buildings with "solar" design. This is not enough to draw statistical conclusions for the total population of passive solar office buildings. It can nevertheless be said that these three buildings are of the same average size and located in similar climates as the other 61 audited office buildings.

They are more recent (5 years on the average when audited) than the other ones (12 years) and use much less energy per square meter floor area than the remaining buildings: 83 kWh/m² against 229 kWh/m².

Figure 2: Passive solar office building in the Netherlands

Two of them are in the Netherlands. One of these was designed as a sustainable, energy saving (70% below standard), human friendly building (Figure 2). It is relatively small (gross floor area of 2000 m^2), with a strong integration of building technique and systems (a.o. HVAC system). The building has an atrium, photovoltaic cells and solar collectors, and is equipped with balanced ventilation (VAV) using displacement flow in the office rooms. Much attention is given to energy saving systems, using a ground coupled (aquifer) heat pump system. Further characteristics are:

- optimisation of volume and surface area

- 90 m^2 photovoltaic panels
- demonstration project for LON (local operating network) technology.

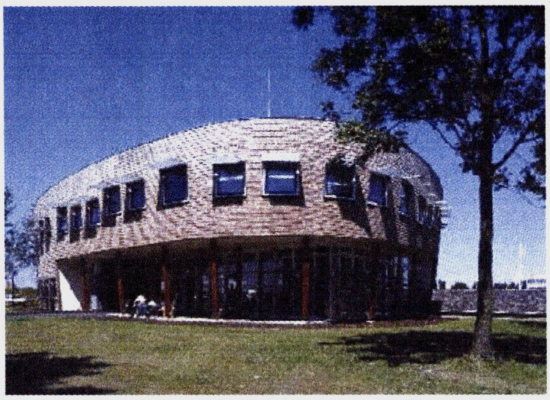


Figure 3: Low energy, solar office building in the Netherlands

The second Dutch building is an example project for sustainable and energy-efficient building (Figure 3). It is also a small office building (gross floor area of 1800 m^2, divided over 3 floors). There are 50 workplaces in office rooms located around an atrium in the centre of the building. On top of the atrium are photovoltaic cells and solar collectors, providing shading while keeping sufficient daylight entering the building. The envelope is better insulated than standard Dutch office buildings. The building is ventilated in a natural way, using self-regulating grills (constant air flow independent of wind pressure) in the facade and a chimney for the stack effect. Heating is provided by a heat pump taking heat from a nearby canal.

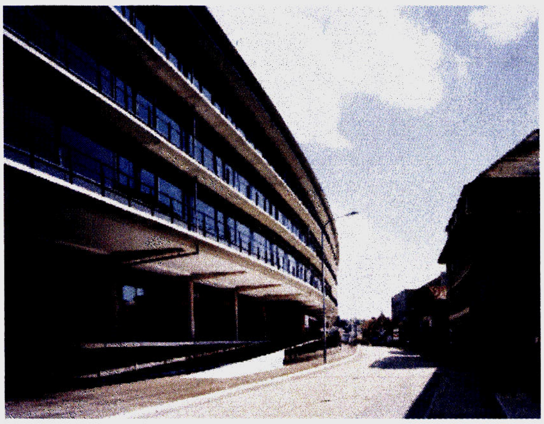


Figure 5.4: S-E façade of the Swiss passive solar office building.

The third audited solar office building is located in Switzerland. Built in 1998 to bring the best possible comfort to the occupants with a minimum energy use, this building has large passive solar gains. Good thermal insulation as well as a hybrid ventilation system with heat recovery from exhaust air and computer centre lead to a total energy performance index lower than 100 kWh/m² floor area. Passive cooling by natural ventilation improves summer comfort in more than 80% of the space. The remaining 20% are spaces that have large internal gains (meeting rooms) and mechanical cooling. The source of energy for heating is natural gas with a significant contribution of 120 m² thermal solar collectors with seasonal heat storage.

The narrow plan facilitates air distribution in the warm season, as the air that enters through the windows is evacuated by central staircases.

The perceived comfort and air quality are the same in both building groups (solar or not) and the BSI in two of the solar buildings are among the best found in this audit. The BSI of the third solar office building is also better than the average of all buildings.

5.2 Apartment buildings

For lack of space, only three of the audited solar apartment buildings are described here.

One of the Portuguese passive solar buildings was built in 1998 integrated in the EXPO'98 site in Sevilla. It takes into account orientation, good external insulation as well as passive solar systems (direct gain and Trombe walls) and it has a central solar water heating system with a natural gas boiler as auxiliary for both hot water and heating. About half of the apartments do not have heating systems installed or connected.

Figure 5: Passive solar building on the Expo98 site in Sevilla

Another Portuguese passive solar building was awarded 1st prize of the PLEA 88 international design competition.

A block of three passive solar buildings was constructed in 1996 in Denmark, with a total of 40 apartments in an open green area. The buildings were constructed based on a new industrial flexible building concept, with good sound insulation. Focus was on building quality, design, indoor climate and installations, durability, ecology. The energy performance index is 126 kWh/m^2y, including 6 MJ/m^2y for electricity.

Table 4 compares some interesting characteristics of buildings with and without solar design or solar systems.

Table 4: Average characteristics of the solar apartment buildings compared to the non-solar ones.

Solar design or devices?	Yes	No	Sign.
Number of buildings	12	72	
Year completed .	1988	1987	N/S
Number of storeys above ground .	4.7	6.9	***
Total treated floor area [m2] .	4649	7576	***
Typical number occupants .	100	245	***
Mean outdoor temperature in winter	8.4	5.3	***
Energy performance index [kWh/m²]	108	188	***
Electricity/floor area [kWh/m²] .	22	26	N/S
Building symptom index BSI	0.98	1.01	N/D
Comfort overall in summer†	2.83	2.81	N/D
Comfort overall in winter†	2.68	2.83	N/S
Air quality in summer†	2.77	3.00	*
Air quality in winter†	2.75	2.99	**

†: Scale goes from 1, satisfactory, to 7, unsatisfactory.

The solar buildings have the same age as the others, but are, on the average, significantly smaller. Their area per occupant is however larger (46.5 against 31 m²/habitant). Their winter external temperature is higher than that of the other buildings, even if four of these buildings are in Denmark.

The energy performance index of solar buildings is, as expected, much smaller than that of the other buildings. The energy use per occupant is also smaller, but not in the same extent, than that of the other buildings. There is however one exception among the audited solar buildings, which uses as much as 307 kWh/m². This building does not have a passive solar design but an active solar system.

No difference is observed between the two groups for BSI and comfort, but air quality is perceived slightly better in "solar" buildings.

6 CONCLUSIONS

As expected, energy performance is improved by installing heat recovery in the ventilation system, and this installation does not change comfort and well being. Winter comfort is even improved in apartment buildings.

Buildings with passive solar design present the best energy performance indices among the audited buildings. The perceived comfort, air quality and well being are the same or better in solar buildings than in the others.

Only a design taking account of all architectural stakes - adaptation to environment and climate, space layout, structure, indoor environment quality and environmental impact - can result in a healthy, comfortable and energy efficient building. Passive solar architecture has the advantage that a careful design is paramount for success, and this may be the very reason why, among all the buildings audited within the HOPE project, most solar buildings are in the top group.

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