MASTERARBEIT

A COMPARISON OF ENERGY AND ENVIRONMENTAL PERFORMANCE OF PASSIVE AND LOW-ENERGY HOUSES

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einer Diplom-Ingenieurin

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1. INTRODUCTION

1.1. Summary

The present thesis is directed to the analysis of the indoor environmental conditions and the energy performance of two energy-efficient apartment houses in Vienna. The first of which is a passive house and the second one is a low-energy house. Both are located in Dreherstrasse, Vienna and were developed simultaneously by the same companies. Building materials and dimensions are comparable; floor plans deviate insignificantly. The main difference between the two blocks (other than the higher degree of thermal insulation in the passive building) lies in the ventilation system: passive buildings deploy controlled ventilation, whereas the low-energy buildings rely mostly on user-operated natural (window) ventilation. Thus, it is reasonable to compare these two buildings with respect to indoor climate and energy performance without the influence of parameters which are difficult to be introduced to the calculations such as different wall materials or different weather situations.

From all factors affecting indoor climate temperature, relative humidity and carbon dioxide-values were measured over a period of five months. Temperature and relative humidity are parameters that significantly influence people's comfort in a room. Likewise high values of CO_2 concentrations may make people feel uncomfortable and potentially cause loss of concentration during daytime and bad sleep during the night.

Upon termination of the measurements, the inhabitants of both buildings were interviewed to find out if they are satisfied with the air quality. As passive houses require active operation of the ventilation system by the inhabitants themselves, it is important to know if these systems allow easy handling. Additionally, the buildings were compared in view of energy performance, CO_2 emissions and costs.

The results suggest that both buildings perform well. However, passive apartments turned out to perform slightly better with respect to indoor environmental conditions. They also consume less energy during operation time, but involve slightly higher initial (construction) costs. Moreover, the inhabitants in both building types are generally satisfied with indoor conditions, building systems and living situations.

1.2. Motivation

Environmental issues are of growing concern and our huge energy consumption is one major contribution. In times of high energy prices not only ecological but also economical reasons make us think about energy efficient housing. Passive and Low-Energy houses are rather new types of buildings, which makes it even more important to scrutinize their performance. To compare passive and low-energy buildings objectively, reliable information regarding their actual performance (energy, indoor climate, environmental impact, cost) would be more helpful than ideological pronouncements. Thus, the present work's contribution to this discussion circles around a comparison of low-energy and passive buildings based on empirical data.

Air quality is a major factor in determining the feeling comfort in a room. Therefore, in the construction of new energy-efficient houses highest importance is to be attached to this fact in order to ensure that the residents are satisfied living there.

In the past, control of indoor environmental factors has mainly been provided using energy-intensive building technologies (Mahdavi and Kumar, 1996). In contrast to that, passive houses provide controlled environmental conditions in an energy-saving way. However, the performance of the ventilation system has to be analyzed. Thus, the comparison of the performance of a ventilation system in a Passive house and a naturally ventilated indoor environment in a comparable Low-Energy house is to be performed.

1.3. Background

In the following, a short introduction to recent work and research on passive house and low-energy house technologies as well as indoor environmental conditions in energy efficient buildings will give an overview of the established state-of the-art.

1.3.1. Passive house and Low-energy house

There are varying definitions for the terms “passive house” and “low-energy house” in different countries; in Austria these are defined in OENORM (2007a, pp.13-14). The definition of low-energy houses reads as follows:

“9.1 Deklaration von Niedrigenergie-Gebaeuden: Gebaeude, bei denen der gemaess OENORM B 8110-6 ermittelte Heizwaermebedarf in Abhaengigkeit von der charakteristischen Laenge lc gemaess Tabelle 7 erreicht bzw. unterschritten wird, duerfen als Niedrigenergie-Gebaeude bezeichnet werden.

Tabelle 7 – Hoechstzulaessige $HWB_{BGF,nE\text{-}WG,Ref}$-Werte und $HWB^*_{V,nE\text{-}NWG,Ref}$-Werte fuer Niedrigenergie-Gebaeude

Waermeschutzklasse	*$HWB_{BGF,nE\text{-}WG,Ref}$-Werte*	*$HWB^*_{V,nE\text{-}NWG,Ref}$-Werte*
Niedrigenergie-Gebaeude	*≤17 x (1 + 2,5/lc)*	*≤5,76 x (1 + 2,5/lc)*

Wenn die charakteristische Laenge lc < 1,0 ist, so ist der hoechstzulaesige Wert mit lc = 1,0 zu rechnen.“

The above definition holds that a building may be declared as a low-energy house if its annual heating demand is equal or less than 17*(1+2.5/lc); wherein lc denotes the characteristic length which is calculated the heated volume divided by the surface area of the building.

On the other hand passive houses have not yet been comprehensively defined in OENORM (2007a); however recommended values have been established:

“9.2 Deklaration von Niedrigstenergie-Gebaeuden

Gebaeude, bei denen der gemaess OENORM B 8110-6 ermittelte Heizwaermebedarf in Abhaengigkeit von der charakteristischen Laenge lc gemaess Tabelle 8 erreicht bzw. unterschritten wird, duerfen als Niedrigstenergie-Gebaeude bezeichnet werden.

Tabelle 8 – Hoechstzulaessige $HWB_{BGF,nstE\text{-}WG,Ref}$-Werte und $HWB^*_{V,nstE\text{-}NWG,Ref}$-Werte fuer Niedrigstenergie-Gebaeude

Waermeschutzklasse	*$HWB_{BGF,nstE\text{-}WG,Ref}$-Werte*	*$HWB^*_{V,nstE\text{-}NWG,Ref}$-Werte*
Niedrigstenergie-Gebaeude	*≤10 x (1 + 2,5/lc)*	*≤3,33 x (1 + 2,5/lc)*

Wenn die charakteristische Laenge lc < 1,0 ist, so ist der hoechstzulaesige Wert mit lc = 1,0 zu rechnen.

9.3 Deklaration von Passivhaeusern (Wohngebaeude)

Das Passivhaus ist im Bereich der Niedrigstenergie-Gebaeude angesiedelt, allerdings wird dabei der Entfall eines Haupt-Heizsystems angestrebt. In der Regel ist dazu ein HWBBGF,Ref-Wert von 10 kWh/m2a zu unterschreiten. Die tatsaechliche Passivhaus-Tauglichkeit ist mit geeigneten Methoden nachzuweisen. Der n50-Wert < 0,6h-1 ist einzuhalten.“

The before definition says that a building may be declared as a very-low-energy house if its annual heating demand is equal or less than 10x (1+2.5/lc). The characteristic length lc is again defined as the heated volume divided by the surface area of the building. Moreover, the definition holds that a passive house comes close to a very-low-energy house, the difference being that passive houses lack a main heating system. In general, this implies that the annual heating demand has to be equal or less than 10kWh/m^2. Also, the actual suitability for passive house technologies is to be demonstrated by adequate means.

However, it is a myth that there has to be no heating system at all, because the heating demand of 15kWh/m^2 has to be provided. Additionally it is of major importance to take the ratio between surface and volume of the building into account (Schoeberl et al. 2009a).

The definition of passive houses provided by “Passivhaus Institut Darmstadt (2009)” relies on the following criteria: The annual heating demand must be equal or less than 15kWh/m^2, the heat load must be equal or less than 10W/m^2, the primary energy consumption must be equal or less than 120 kWh/m^2a and the air tightness n50 has to be equal or less than 0.60/h.

Tools for verifying that a building fulfills passive house standards include the “PHPP – Passivhaus Projektierungs Paket” that was developed by “Passivhaus Institut Darmstadt”.

Hutter et al. (2005) identify three main characteristics of passive houses: good heat insulation, compact form and air tightness. Passive houses rely on a ventilation system that supplies the rooms with fresh, heated up air and removes used air.

1.3.2. Indoor environmental conditions

Indoor air quality is one of the most important factors affecting people´s feeling of comfort inside rooms (Feist et al. 2003b). Hutter et al. (2005) mention that people have been interested in indoor air quality (IAQ) for a very long time. In the ancient world people already attempted to improve indoor air quality to avoid health problems and unpleasant smells.

In recent times IAQ has become an important issue as reports about the so-called Sick Building Syndrome (SBS) began to spread.

SBS is characterized by an unspecific discomfort accompanied by headache, mucous membrane irritation, allergies, etc (Wikipedia, 2009). It is associated with a specific workplace or residence. The cause for SBS is probably related to poor indoor air quality due to inadequate HVAC (Heating, Ventilation and Air-Conditioning) systems and outgassing of building materials. SBS was mainly found in connection with office buildings where the windows could not be opened.

Plenty of empirical evidence shows that many mechanical building services do not provide the required range of environmental conditions (Mahavi and Kumar, 1996).

Hutter et al. (2005) claim that the air change rate has a significant influence on the concentration of indoor air components and also affects physical parameters such as temperature and relative humidity. Hence, an increase of the air change rate might improve the IAQ. In old buildings, the air change rates are rather high because of leaky windows. New buildings, in particular low energy buildings, have to be built completely airtight which results in a very low air change rate. Improved insulation and air-tightness however, may negatively affect the indoor air quality, as Feist et al. (2003b) assert.

A Canadian study cited by Hutter et al. (2005), compared 52 energy efficient buildings using controlled ventilation with 53 energy efficient buildings that were naturally ventilated in view of SBS. The inhabitants were interviewed right after moving in and again one year later. In the case of buildings with controlled ventilation, the reduction of SBS cases over time was more significant than in the other buildings. It is assumed that the higher air change rate in the controlled ventilated buildings ensures a faster reduction of pollutant concentrations that are caused during construction.

A study in Nuernberg which was also mentioned by Hutter et al (2005) analyzed the indoor air quality in four passive houses over a period of two years. The results revealed that during the construction phase, the concentration of pollutants was extremely high but decreased quickly afterwards. After a few months had passed, the observed concentrations were apparently much lower than in houses built of the same materials but without controlled ventilation system.

Indoor air is prone to pollution from various sources as Hutter et al. (2005) claim. These sources include outgases of building materials, bacteria due to unhygenic situations, pollen, anthropogenic pollutants etc. The latter comprise acetaldehyd, allylacohol, acetic acid, phenol and amylacohol. CO_2 is considered to be a leading indicator of all anthropogenic pollutants because an increase thereof in indoor air correlates to an increase of the intensity of smell due to human exhalation.

1.3.2.1. CO_2 Concentration

Hutter et al. (2005) hold that a high CO_2 concentration may indicate poor indoor air with regard to hygienic conditions. The CO_2 concentration mainly depends on room occupancy, room size and air change rate. As can be seen from Table 1, the human CO_2 exhalation rate changes with physical activity.

Table 1. Human exhalation of CO_2 (Hutter et al. 2005)

Literature	Unit	Value	Comment
Rietschel (1994)	[L/h]	20,4	sitting activity, standing relaxed
	[L/h]	27,2	standig activity
Witthauer, Horn, Bischof (1993)	[L/h]	12	calm condition
	[L/h]	18	sitting activity
	[L/h]	180	heavy labour
Recknagel, Sprenger, Schramek (1999) VDI 4300 Bl. 9 (2003)	[L/h]	20	sitting activity
	[L/h]	15 – 20	sitting activity
	[L/h]	20 – 40	unexhausting work
	[L/h]	40 – 70	mediumheavy work
	[L/h]	70 – 110	heavy labour
ASHRAE (1989)	[L/h]	18	office work

Medical studies suggest that CO_2 concentrations of lower than 10.000ppm do not lead to severe health problems but have a negative impact on probands' concentration, effectivity of labour and feeling of comfort (in particular vulnerability to headache, dry mucous membrane etc.). Higher concentrations of CO_2 however, might cause breathing problems; cases of unconsciousness were reported for values of above 100.000ppm (Hutter et al. 2005).

Hutter et al. (2005) submit that in general, no upper threshold for CO_2 concentration can be defined however, various critical values have been developed in the literature. The best known thereof is the Pettenkofer-value (1858) which is 1000ppm for residences. On the other hand, Huber and Wanner (1982) postulate that the limit when people feel uncomfortable lies at 1500ppm. Generally IAQ gradually decreases when the CO_2 concentration exceeds 700ppm. The *Arbeitskreis Innenraumluft* has suggested a classification of IAQ with respect to CO_2 concentration which was reported in 2004 (Table 2).

Table 2. Classification of IAQ due to CO_2 Concentration (Hutter et al. 2005)

Indoor Air Quality	CO_2 Concentration	
	Above Outdoor Air	Absolute
High	<=400ppm	<800pm
Medium	>400-600ppm	800-1000ppm
Moderate	>600-1000ppm	1000-1400ppm
Poor	>1000-1500ppm	1400-1900ppm
Very Poor	>1500 ppm	>1900ppm

Horn et al. (2009, pp.143-148) claim in their recent work on measurements of longterm stable CO_2 concentrations that pre-set air supply systems do not necessarily ensure the actual air demand. Disadvantageously, a gap between air demand and air supply on the one hand may give rise to heat energy loss or on the other hand may negatively affect the indoor air quality. The air demand can be calculated from constantly measuring the CO_2 concentration.

Horn et al. (2009, pp.143-148) also mention infrared (IR) absorption as useful concept for measuring CO_2 concentrations. Drawbacks of these sensors involve relatively high costs, limited precision and sensor problems in longterm use. An IR optical gas sensor typically consists of an IR radiation source, a cuvette containing the measuring gas and an IR sensitive detector.

1.3.2.2. Relative Humidity

In general, the relative humidity of indoor air should lie between 40 and 60% as Hutter et al. (2005) claim. Very low humidity can lead to dry mucous membrane and susceptibility for infections, whereas very high humidity can abet the growth of mould fungus and acarians. Starting from 70% relative humidity people also feel uncomfortable.

Buildings with ventilation systems usually have comparatively high air change rates. In winter when outdoor humidity is very low this can lead to values for relative humidity of less than 30% which has no serious effect if it occurs only for a few days in winter. The filtered air is usually very clean and does not affect people’s health. However, in case the relative humidity remains at a very low level over a longer period of time, means should be adopted to increase it. Air saturators and room fountains have a positive effect but need to be cleaned carefully. Another option is to decrease the air change rate which should be done by experts (Hutter et al. 2005).

Energy efficient buildings without ventilation systems naturally tend to have rather high relative humidity values because they are tightly built so that the air change rate is comparatively low as Hutter et al. (2005) mention. As a consequence, growth of mould on the exterior walls as well as acarians is accelerated. Relative humidity can be decreased by ventilating more often, turning on the heating, avoiding aquaria and using a dryer instead of hanging up wet clothes.

1.3.2.3. IAQ in energy-efficient buildings

Rongen (2009, pp.261-273) enumerates the following advantages of controlled ventilation in passive houses: high surface temperatures prevent uncomfortably high air velocity in the areas of exterior walls; filtered fresh air helps people suffering from allergies; also bad smells caused by cooking etc. are removed in a comparatively short period of time.

Rongen (2009 pp.261-273) also mentions a nursing home for elderly people in Mönchengladbach in which urin smell is largely prevented by using a controlled ventilation system.

It has been shown that pupils attending schools built in passive house technologies are apparently better concentrated which can be attributed to lower CO_2 concentrations (Rongen, 2009 pp.261-273).

A study by Peper (2009, pp.313-318) concerns a comparison between a renovated passive house and a renovated LEH residence building. The PH has controlled ventilation whereas the LEH is ventilated naturally. In three apartments of each building relative humidity and CO_2 concentration were measured.

The air change rate turned out to lie between 0.35 and 0.47 h^{-1} in the PH and between 0.1 and 0.26 h^{-1} in the LEH. A higher air change rate led to higher heating demand. Even if the windows were open for long periods, between 2.4 and 6.2 hours a day in winter, the relative humidity and CO_2 values were too high in the apartments of the LEH. Relative humidity was 5% higher in the LEH than in the PH. In the latter, relative humidity occasionally fell below 30% probably because of a rather high temperature of about 23°C. In one apartment in the LEH the average relative humidity was 60%, which can be attributed to the comparatively short window opening times. In winter the CO_2 values in the PH were above 1500 ppm 8% of the time whereas in the LEH the CO_2 concentration was above that value 21% of the time (Peper, 2009, pp.313-318).

In summer, the indoor air quality is usually better than in winter. One problem that predominantly occurs in summer is the overheating of buildings. According to OENORM (1999), a room is considered to be overheated when its temperature lies above 27°C in daytime or exceeds 25°C during the night.

Feist et al. (2003, a) states that a high air change rate helps to reduce the room temperature if the outdoor temperature comparatively is lower. In summer both in the PH and in the LEH ventilation is mainly performed through the windows. The thick insulation of these energy efficient buildings has a positive effect on avoiding overheating. He also mentions that it is possible to use the ventilation system of passive houses not only in winter but also in summer; however an exclusive use of the ventilation system is hardly feasible on hot days. This can be attributed to the air change rate that would have to lie between 0.7 and 2.0 h^{-1} which would require an eight times higher energy consumption of the ventilation system. Apart from that, common ventilation systems are not built for such high air change rates but merely for an air change rate between 0.3 and 0.4 h^{-1}.

Feist elaborates several factors that can help to avoid overheating in summer: first, ventilation through tilted windows is very effective. Moreover, ventilation at night when it is cooler outside affects the indoor temperature positively. Exterior shading and reduction of internal heating sources in summer also have positive effects. Much building mass and turning off the heat recovery usually help to prevent overheating in rooms. Ultimately, cross ventilation and a vertical ventilation over at least two levels are potentially helpful in summer (Feist et al. 2003a)

During the heating period different strategies have to be pursued to achieve efficient ventilation. In buildings lacking ventilation systems, the optimal way of ventilation is shock ventilation every 6 hours performed 4 times a day as Feist et al. (2003b) reveal.

2. METHOD

2.1. Selection of the objects

2.1.1. General information

The selected buildings are located in Vienna, Dreherstrasse 66, 11th district of Vienna. The site lies 175m above sea level.

Figure 1. Map of Vienna (Googlemaps, 2009)

The project was finished in September 2007, the first inhabitants moved in soon thereafter.

The companies which were involved in the project are shown in

Table 3.

Table 3. Involved Companies (Wagner, 2008)

Project organizer	BUWOG, Bauen und Wohnen GesmbH Hietzinger Kai 131, 1130 Wien
Architect	Guenter Lautner Schoenbrunnerstrass 84, 1050 Wien
HVACR	Vasko & Partner, DI Christian Steininger
Consulting	Schoeberl & Poell
Building Physics	DI H.J.Dworak
Building Company	UNIVERSALE Hochbau Wien

2.1.2. Objects

The site contains five buildings, one of which being a passive house with 27 apartments; the remaining four buildings are low-energy houses containing a total of 111 apartments.

The apartment sizes range from 48 to 120 m^2 living space. Each apartment has one to four rooms. Some apartments are developed as maisonettes or lofts.

Figure 2. Dreherstrasse 66

The buildings are named after fruits or vegetables; from northwest to southeast they are called pear, melon, aubergine, bean and mango. All building floor plans are free forms and differ only marginally. A specific drop-form was chosen because of its energy-efficiency. Thereby the insulation-thickness can be reduced by one-third compared with regular building forms. The forms and the way the buildings are placed in relation to each other minimize the north facade areas. According to the building forms, an interesting outdoor space is generated.

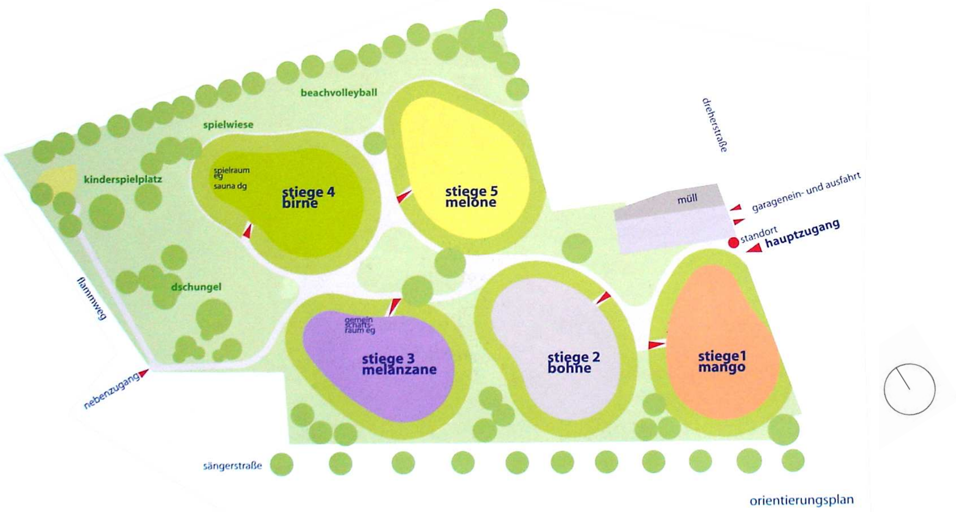


Figure 3. Map of the site (Announcement, 2009)

The main entrance as well as the gateway to the basement garage are situated at the east side facing Dreherstrasse. At the northwest end of the site, there is a volleyball court and a playground for children. The side entrance which can only be passed by inhabitants is also situated in the west.

The private gardens surrounding all buildings on the ground floor belong to the apartments on the ground floor. In the basement of each building there are laundry rooms and storage rooms for bicycles and strollers. The mechanical equipment rooms are also located in the basement. Each building is equipped with an elevator. Some buildings are equipped with a sauna or a common room for the inhabitants.

2.1.3. Selected Objects

The building at the northeast, called "melon", is the passive house. The remaining four buildings are low energy houses; the building at the southeast is called "mango". For these two buildings measurements of temperature and relative humidity already existed before this work. Hence, it was reasonable to use these values as a reference for measurements of temperature, relative humidity and CO_2 of these two buildings.

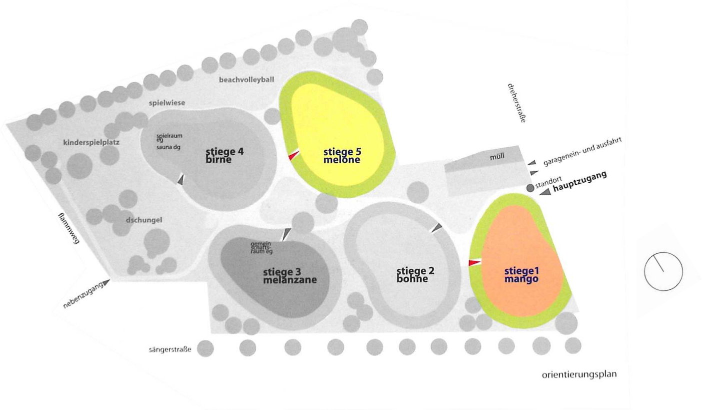


Figure 4. Map of the site (Announcement, 2009)

In each targeted building, measurements were conducted in one small apartment with one inhabitant and one larger apartment with 3 or 5 inhabitants. Table 4 shows an overview of the selected apartments displaying information about the area, number of inhabitants, main orientation, U-values of external walls and U-values of the windows. In the following, the apartments are referred to as PH_1, LH_1, PH_2 and LH_2.

Table 4. Overview of the selected apartments

Block	Apartment	Area [m^2]	No. of residents	Main orientation	U-value external walls [$W.m^{-2}.K^{-1}$]	U-value windows [$W.m^{-2}.K^{-1}$]
Passive	PH_1	59.4	1	West	0.13	0.8
	PH_2	89.5	3	West, North, East	0.13	0.8
Low-energy	LH_1	51.6	1	East	0.40	1.34
	LH_2	84.5	5	West	0.40	1.34

2.1.3.1. Passive house

Both of the selected apartments in the passive house are situated on the second floor of the building.

Passive house, apartment 1

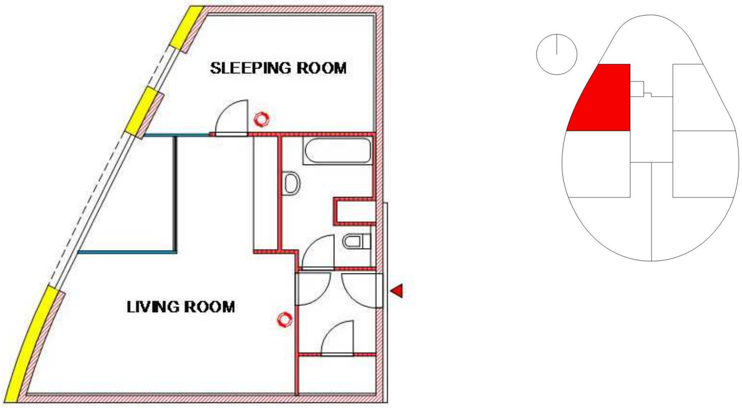


Figure 5. Floor Plan, PH_1

The apartment, sized 59.35 m^2, is occupied by one resident. The apartment is oriented to the west and is equipped with one standard sized window in the sleeping room and one oversized window in the living room. In the sleeping room the measuring devices were placed on the nightstand right hand side of the door. The sensors in the living room were placed on a dresser left hand side of the entrance door. The floor plan (Figure 5) shows the exact sensor locations.

Figure 6. PH_1 living room

Figure 7. PH_1 sleeping room

Passive house, apartment 2

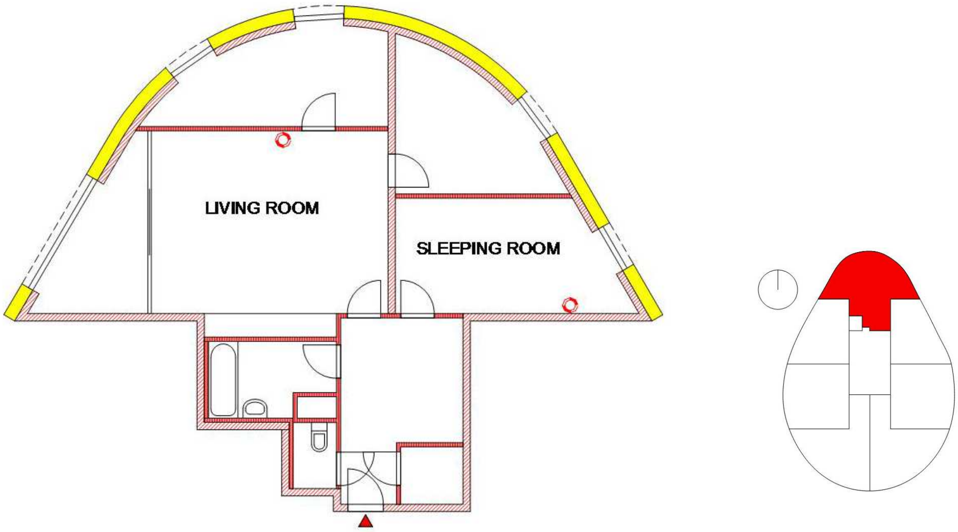


Figure 8. Floor Plan PH_2

Three residents live in the apartment of 89.47 m^2. Parts of the apartment are oriented to the east, west and north. It is equipped with standard sized windows in the sleeping rooms and the workroom and one oversized window in the living room. The measuring devices are located in one of the sleeping rooms on a dressing table. The sensors in the living room were placed on a rack beside the couch. Figure 8 shows the locations of the measuring devices.

Figure 9. PH_2 living room

Figure 10. PH_2 sleeping room

Superstructure:

The superstructure of the passive house is different from a standard building because of the need for achieving a very low heat load. The exterior walls consist of 18cm of ferrocement and 30cm of EPS F-15 insulation as Vasko+Partner (2007b) claim. The windows are equipped with high-quality three-panel-glazing and a well insulated frame. The U-value of the windows is 0.8 $Wm^{-2}K^{-1}$ and the g-value is 0.5.

Heating and ventilation:

According to Vasko+Partner (2007b) the passive house is equipped with a mixed central and semi-central ventilation system. A central ventilation device is situated in a mechanical equipment room in the basement. This has the advantage that most of the maintenance can be done without accessing the apartments. The central device has an outdoor-air filter, ventilators for delivery and return air and a highly efficient waste heat recovery.

There are local devices that allow the inhabitants to control the air change rate as well as the temperature, e.g. in a feeling of cold occurs during the winter months. The additional heating can be regulated by a thermostat and heats up the supply air before it enters the rooms (Vasko+Partner, 2007a). The rest heat and the energy for warm water supply are provided by a district heating network. An energy-saving pump is used.

In each apartment the air change rate may be regulated. There are four different levels as shown in Table 5. The devices for regulating temperature and air change rate are illustrated in Figure 11 and Figure 8.

Table 5. Air change levels (Vasko+Partner, 2007b)

	Air change rate [h^{-1}]
Normal	0.45
Party	0.6
Eco	0.3
Off	0.1

Figure 11. Thermostat PH (Vasko+Partner, 2007a)

Figure 12. Air-change regulation PH (Vasko+Partner, 2007a)

Some important factors have to be taken into account when living in such a building. By way of example Vasko+Partner (2007a) mention:

Regular maintenance of the ventilation devices for instance filters.

With respect to ventilation issues a blockage of the gaps on the bottom of each door should be avoided.

The additional heating should not be turned off when leaving the apartment for holidays because otherwise it would take a very long time to heat it up again.

In hot periods the windows should only be opened during the night while in daytime every window should be shaded.

When opening the windows in winter, which is usually not necessary, the inhabitants should perform shock venting instead of tilting the windows to avoid high heating demands.

2.1.3.2. Low-energy house

The targeted Low-energy house is described in the following: Apartment 1 is situated on the second floor of the building and apartment 2 is located on the ground floor of the building.

Low-energy house, apartment 1

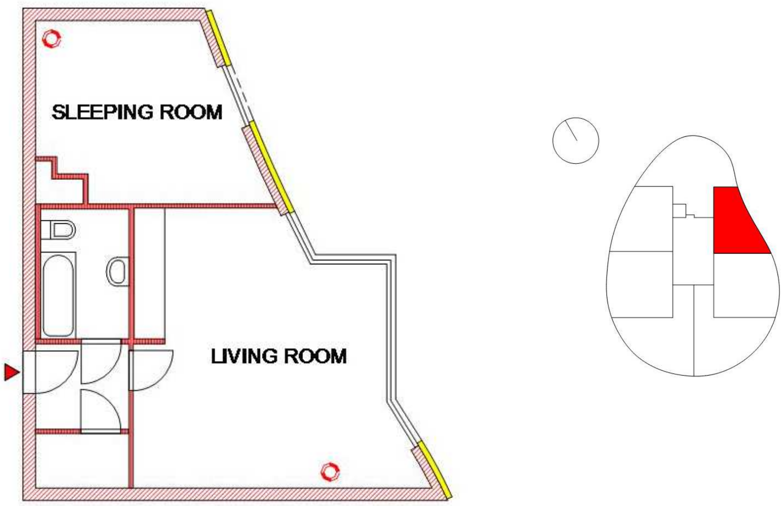


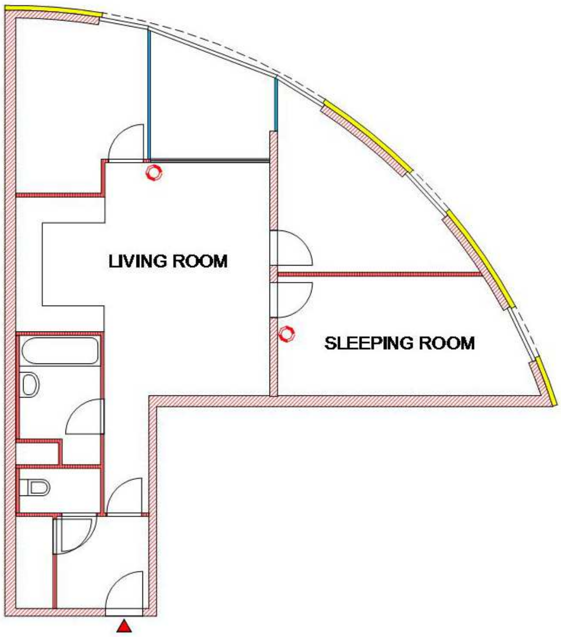
Figure 13. Floor plan, LH_1

The apartment, sized 51.55 m^2 houses one inhabitant. The apartment is oriented to the east and is equipped with a standard sized window in the sleeping room and an oversized window in the living room. In the sleeping room the measuring devices were placed on the nightstand in the corner of the room. The sensors in the living room are located on a dresser. Figure 13 shows the exact locations of the measuring devices.

Figure 14. LH_1 living room

Figure 15. LH_1 sleeping room

Low-energy house, apartment 2



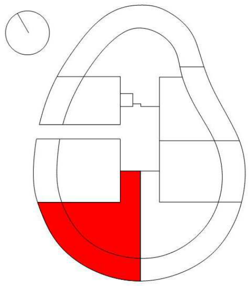


Figure 16. Floor plan, LH_2

The apartment is occupied by five residents and measures 84.50 m^2. The apartment is oriented to the west and is equipped with standard sized windows in the sleeping rooms and one oversized window in the living room. The sensors are placed in one of the sleeping rooms next to the door. The measuring devices in the living room are located on a rack behind the dining table. The precise locations of the sensors, each denoted by a small circle, become apparent from Figure 16.

Figure 17. LH_2 living room

Figure 18. LH_2 sleeping room

Superstructure:

The exterior walls consist of 18cm of ferrocement and 11cm insulation. The U-value of the windows is 1.34 $Wm^{-2}K^{-1}$.

Heating and ventilation:

Low-energy houses usually have no or merely a basic ventilation system. The low-energy building in Dreherstrasse is equipped with a basic ventilation system which provides only a minimal air change rate. Accordingly the apartments have to be ventilated mainly by opening the windows.

The basic ventilation system works as follows: An EHA supply-air device by Krobath Protech GmbH is installed above each window. This device working as a ventilation slot automatically opens and closes depending on measured humidity values. In the open position, a ventilator in the bathroom sucks in air from the interior of the apartment and directs it to the outside. Gaps at the bottom side of each door ensure that the air can stream from one room to another. On the other hand the outdoor air streaming into the rooms is immediately heated up by mixing with the warm indoor air at the ceiling.

The building is heated by a district heating network.

2.2. Measurements

Initially, the environmental conditions in the passive house and the low-energy house were examined. The deployed method involved measuring CO_2 values, temperature and relative humidity in two apartments of each building. In each apartment sensors were placed in the living room and the sleeping room, as these rooms play a crucial role in terms of indoor environmental conditions.

The measurements extended over a period of five months using two different types of measuring devices in each building. The measurements were started in early February and terminated end of June. The chosen period thus includes data from both the heating period with low outside temperatures and the hot period.

The general circumstances of living among the inhabitants are comparable; there was no longer absence during the measuring period. Please note, that we could not obtain any data for apartment 1 of the low-energy house in February and March.

2.2.1. Measuring Devices

The measurements were performed using HOBOs and CO_2 sensors provided by TU Wien as well as data loggers, CO_2 sensors and I-Buttons provided by AEE Intec.

Four HOBOs (Figure 19) were used to measure temperature and relative humidity and each HOBO was connected to a CO_2 measuring device.

The HOBOS were placed in the living room and the sleeping room, preferably on a wall or a desk disposed at a distance from the windows in order to minimize errors. Moreover it was ensured that the HOBOS are protected from water and direct sunlight.

“Greenline” software was used for reading out the data. Every two weeks the HOBOs were read out and the batteries were checked. The data read out from the HOBOs was then saved on a PC.

Figure 19. HOBO

The other types of measuring devices used for this study were provided by AEE Intec (Figure 20).

EE80 sensors measuring CO_2 based on the infrared principle were connected to ELUSB-3 data loggers which logged voltage every five minutes. On the other hand temperature and relative humidity were logged by “Dallas Semikonduktors” I-Buttons every 15 minutes.

The data from the USB-loggers was read out using “EasyLog USB”-software which had to be performed every six weeks. The I-Buttons were read out by AEE Intec and the data was provided for this work.

Figure 20. Devices provided by AEE Intec

2.2.2. Questionnaire

After conclusion of the measurements, the inhabitants were asked to fill out a questionnaire. Two different questionnaires were created; the first one comprising basic questions and the second one including more detailed questions for the inhabitants of the monitored apartments. The questionnaires deal with the inhabitants' satisfaction with energy efficient housing, air quality and the ventilation system.

2.3. Analysis

A legend was created in order to ensure the probands' anonymity and make each situation recognizable at first sight. The legend reads as follows:

Passive house:	PH
Low-energy house:	LH
Apartment 1:	1
Apartment 2:	2
Sleeping room:	SR
Living room:	LR
February:	FEB
March:	MAR
April:	APR
May:	MAY
June:	JUN
Temperature:	T
Relative humidity:	R
CO_2:	C

Example: Low-energy house, apartment 1, sleeping room, March, CO_2:

LH_1_SR_MAR_C

2.3.1. Types of Analysis

Three different types of analysis were used, as will be described in the following.

2.3.1.1. Histograms

Histograms show the actual differences in temperature, relative humidity and CO_2 between each individual apartment for the sleeping room, the living room or the entire apartment. Histograms show frequency distributions (in %) of the data for certain categories called "bins". The bins for the histograms are identical for each situation to make them comparable (see Table 6).

An exception is a winter/summer change in temperature-bins because there are significant differences in temperature that cannot be shown in one bin-case. The winter-bins are used for February, March and April whereas the summer-bins are used for May and June. In order to compare temperature over the whole observation period, another bin-case was created.

A histogram was created for every room and each month and the histograms that are not shown in the results-chapter can be found in the appendix.

Table 6. Bins for histograms

		Bins
Temperature	Entire period	<19 19-20 20-21 21-22 22-23 23-24 24-25 25-26 26-27 >27
	Winter	<19 19-20 20-21 21-22 22-23 23-24 24-25 >25
	Summer	23 23-24 24-25 25-26 26-27 27-28 28-29 >29
Rel. humidity		<25 26-30 31-35 36-40 41-45 46-50 51-55 >55
CO_2		<400 400-600 600-800 800-1000 1000-1200 1200-1400 1400-1600 1600-1800 1800-2000 >2000

The second type of histogram is the so-called cumulative histogram. It displays the data by counting the cumulative number of all the frequencies up to a specified bin. The bins for the cumulative histograms are shown in Table 7.

Table 7. Bins for cumulative histograms

		Bins
Temperature	Winter	<19 <20 <21 <22 <23 <24 <25 >25
	Summer	<23 <24 <25 <26 <27 <28 <29 >29
Rel. humidity		<25 <30 <35 <40 <45 <50 <55 >55
CO_2		<400 <600 <800 <1000 <1200 <1400 <1600 <1800 <2000 <2500

2.3.1.2. Psychrometric charts

A psychrometric chart is a graph in which each point represents a condition in a gas-vapor system with respect to temperature on the horizontal axis and absolute humidity on the vertical axis.

In the psychrometric charts, data points lying within and around the so-called *comfort zone* are shown. The comfort zone is a two-dimensional area that is calculated using temperature and humidity parameters. The data points that lie within the comfort zone are considered as comfortable. The extent of the comfort zone was obtained as follows. For each month the mean outdoor temperature was calculated. This value was used to compute the neutrality temperature and the extent of the comfort zones on psychrometric charts according to Szokolay (2004).

The comfort zone was calculated for the region around Dreherstrasse for each month of the observation period. After calculating the comfort zone, a diagram displaying the comfort zone is generated which is then overlayed with the data points. The percentage of data points that lie within this zone is indicative of the feeling of thermal comfort.

2.3.1.4. PMV and PPD

Calculating the PMV (predicted mean vote) and PPD (predicted percentage of dissatisfied) is an alternative approach in assessing thermal comfort. The predicted mean vote shows people’s feeling of thermal comfort on a scale from minus three to plus three. A negative value indicates that the person is cold while a positive value indicates that the person is hot. Values between -0.5 and 0.5 are considered comfortable. The predicted percentage of dissatisfied shows the percentage of people that are dissatisfied with the thermal situation. PPD cannot drop beneath 5%. If all PMV values lie within -0.5 and 0.5, in this case PPD is 12%. Temperature, relative humidity, air velocity, clothing values and metabolic rates enter these calculations as parameters (Baunetzwissen, 2009).

Our underlying assumptions for the calculation of PMV and PPD are summarized in Table 8. For the purpose of the calculations, mean radiant temperature values were assumed to be equal to the (measured) room air temperatures.

Innova (2004) claims that clothing-values describe the thermal resistance of textiles which is also called “insulation value”. The clo-values chosen for the present calculations take account of typical indoor clothing as well as clothing at night, considering the influences of mattresses and blankets. Also, as shown in Table 8, there are different values for summer and winter.

On the other hand, the metabolic rate identifies the energy released by oxidation processes in the human body which depends on muscular activity (Innova, 2004). Naturally, with regard to the metabolic rate it is distinguished between a condition of sleeping and activity.

Table 8. Assumptions for the calculation of PMV and PPD

		Winter (Feb, Mar, Apr)			Summer (May, Jun)		
Room	Hours	Clo	Met	v [m.s^{-1}]	Clo	Met	v [m.s^{-1}]
SR	22:00 - 8:00	2.5	0.8	0	1.5	0.8	0
LR	8:00 - 22:00	1.0	1.3	0.15	0.5	1.3	0.15

2.3.1.5. Questionnaire

The questionnaire comprises the chapters general information, evaluation of living room and sleeping room as well as evaluation of information. It was analyzed statistically using standard deviation, mean values and averages. Additionally, boxplots were created for selected questions.

3. RESULTS AND DISCUSSION

The results for the beforehand described types of analysis comprising histograms, psychrometric charts as well as PMV and PPD are presented in the following. Furthermore, the central findings are discussed in this chapter.

3.1. Histograms

3.1.1. Overall comparison

In a first attempt differences between the apartments of both buildings with respect to the measured variables over the whole monitoring period in the entire apartments are identified. In the following figures, relative frequencies for each category are shown.

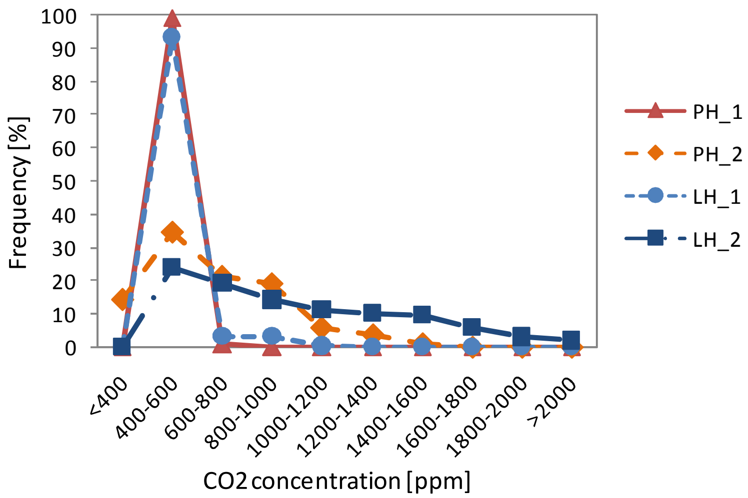


Figure 21. All apartments_both rooms, whole period_C

Figure 21 shows the CO_2 concentrations in the entire apartments over the whole monitored period. It reveals that CO_2 concentrations lie within reasonable ranges in all apartments as only a small fraction of the recorded data points lies above the Pettenkofer threshold of 2000ppm. For PH_1 and LH_1, as well as for PH_2 and LH_2 comparable results are obtained. Nonetheless, it becomes apparent that PH_1 has overall slightly lower CO_2 concentrations than LH_1 and instances of high concentrations in PH_2 are much less frequent than in LH_2.

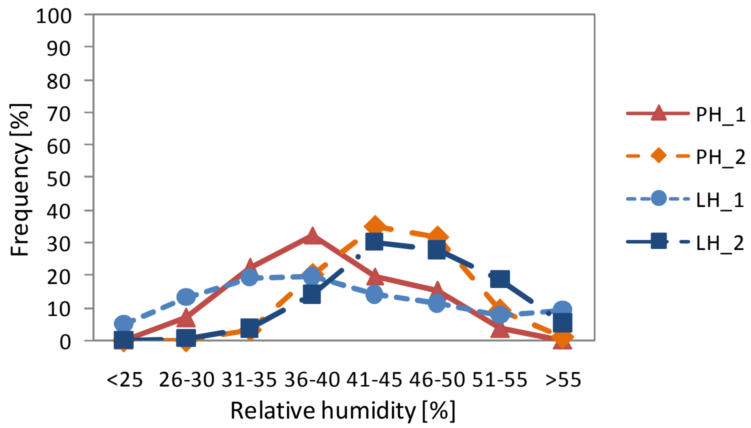


Figure 22. All apartments_both rooms_whole period_R

In Figure 22 the relative humidity values for both rooms during the whole measuring period can be found. It can be revealed that relative humidity values mostly stay within acceptable limits in all the apartments. Relative humidity values vary widely in LH_1 while they are comparatively stable in the other apartments. Both of the larger, more densely occupied apartments PH_2 and LH_2 show higher RH values than the smaller, less densely occupied apartments.

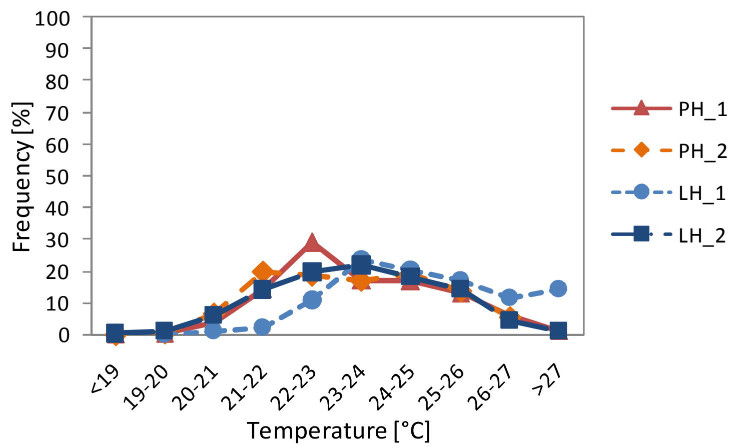


Figure 23. All apartments_both rooms_whole period_T

Figure 23 shows the values for temperature in the entire apartments over the whole observation period. It suggests a similar distribution pattern in all apartments, with the exception of LH_1, which displays a shift toward higher temperatures.

3.1.2. Detailed comparison

In the next step, seasonal changes are examined and the monitored rooms are observed individually. Effects of changing outdoor conditions on the indoor air quality as well as the differences between the conditions in the living room and the bedroom are analyzed.

In the detailed comparison the diagrams are shown as cumulative histograms which show cumulative relative frequencies up to a certain bin.

The following figures (Figure 24 - Figure 28) show the course of the measured CO_2 concentrations from February to June in the sleeping rooms of the selected apartments.

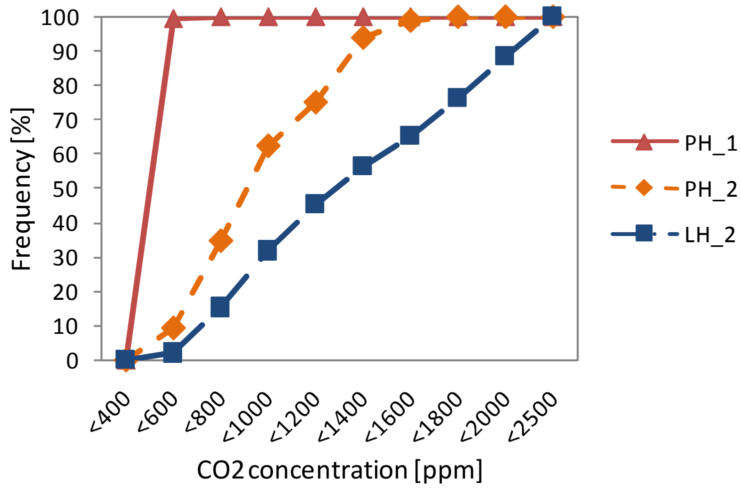


Figure 24. All apartments_SR_FEB_C

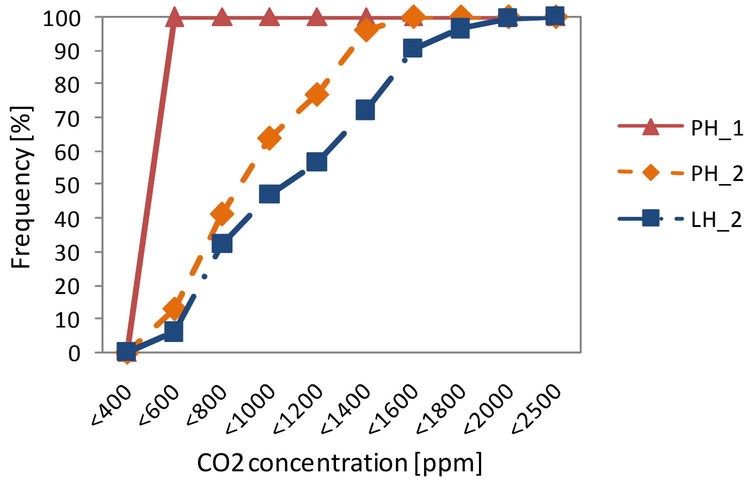


Figure 25. All apartments_SR_MAR_C

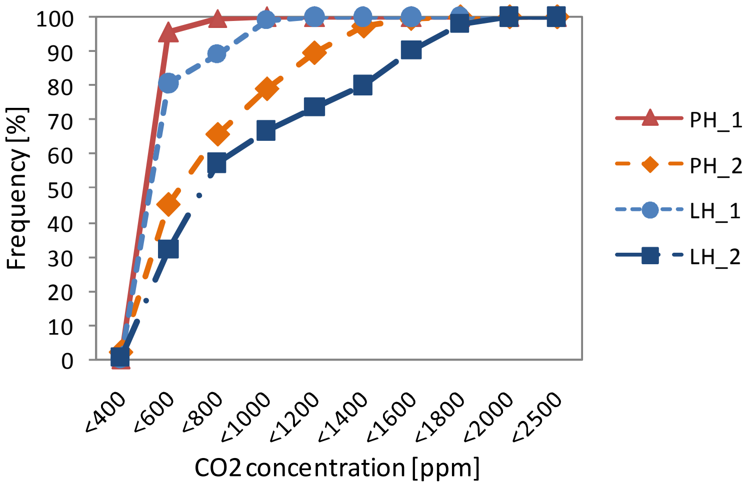


Figure 26. All apartments_SR_APR_C

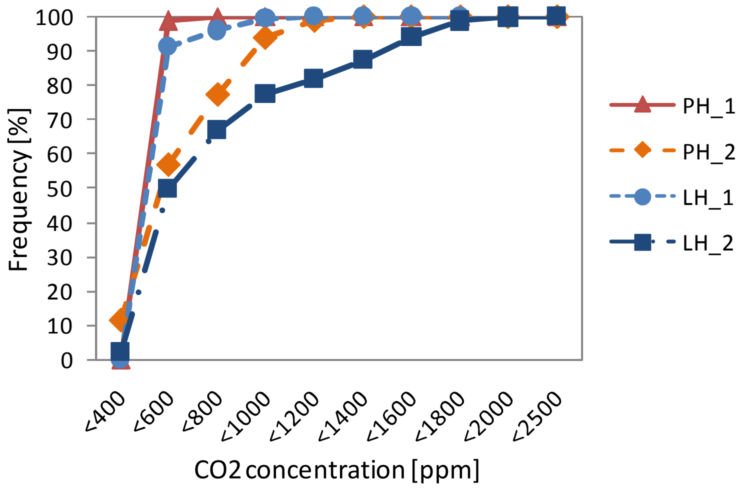


Figure 27. All apartments_SR_MAY_C

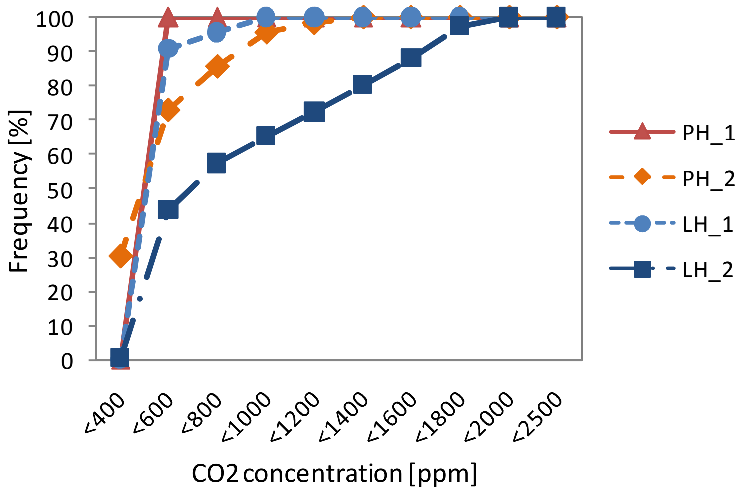


Figure 28. All apartments_SR_JUN_C

Figure 24 to Figure 28 reveal that the CO_2 concentration distributions show a shift towards lower CO_2 concentrations in the course of the observation period in all the sleeping rooms. In other words, the CO_2 concentrations decrease with rising outdoor temperatures. This can be attributed to the ventilation behavior of the residents, who perform window ventilation more frequently during the warmer period.

Both single apartments PH_1 and LH_1 have very low CO_2 concentrations over the entire observation period, whereas in the more densely occupied apartments PH_2 and LH_2 higher CO_2 concentrations are detected. Therefore, it can be revealed that CO_2 values are significantly dependent on the number of inhabitants. Single apartments have lower CO_2 concentrations than more densely occupied apartments.

Taking a closer look at the comparable apartments PH_1 and LH_1, it becomes apparent that the concentration of CO_2 is slightly lower in PH_1 during the entire monitoring period. Furthermore, PH_2 shows significantly lower CO_2 values than LH_2 in particular for high concentrations. The most significant differences can be detected in the colder months in the sleeping rooms during the night. This may be attributed to the controlled ventilation in the passive house apartments that provides the rooms with fresh air while the low-energy sleeping rooms are not ventilated during the night.

Figure 24 shows that in February, the coldest month of the monitored period, the CO_2 concentrations in the large PH sleeping room did not rise above 1600 ppm most of the time while in the large LH sleeping room the CO_2 concentration was lying above 2000 ppm 11.5% of the time. The reason for that is probably the ventilation system of the PH which constantly exchanges the air.

The monthly histograms that show CO_2 concentrations in the living rooms (see appendix) show comparable results as the before analyzed CO_2 histograms for the sleeping rooms. In accordance with the case of the sleeping rooms, the single apartments perform very well over the whole monitored period and in all the living rooms and the CO_2 concentration decreases in all apartments in the course of the observed months. The PH apartments perform slightly better than the comparable LH apartments.

From these results it can be asserted that with respect to CO_2 concentrations, the use of a ventilation system is definitely advisable, especially for densely occupied apartments in particular during the cold months.

The following figures (Figure 29 - Figure 33) show the course of the measured relative humidity values from February to June in the sleeping rooms of the selected apartments.

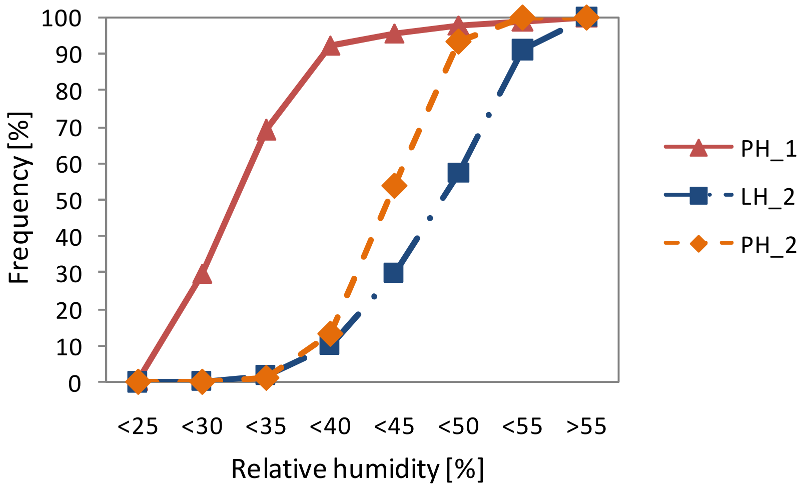


Figure 29. All apartments_SR_FEB_R

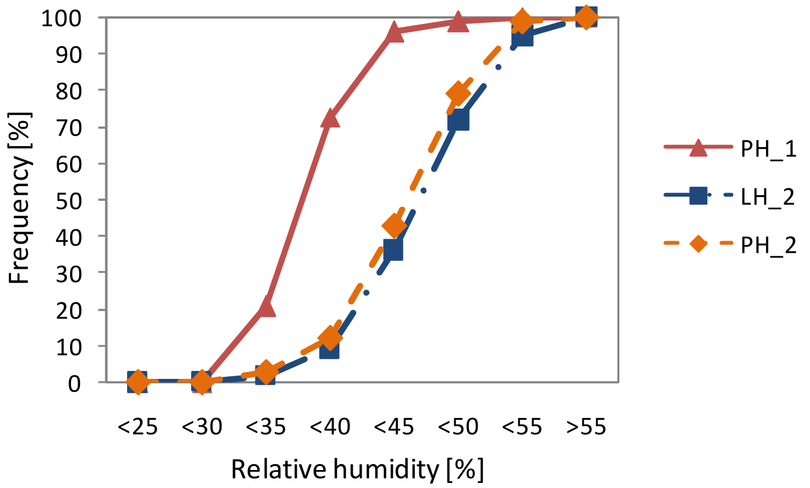


Figure 30. All apartments_SR_MAR_R

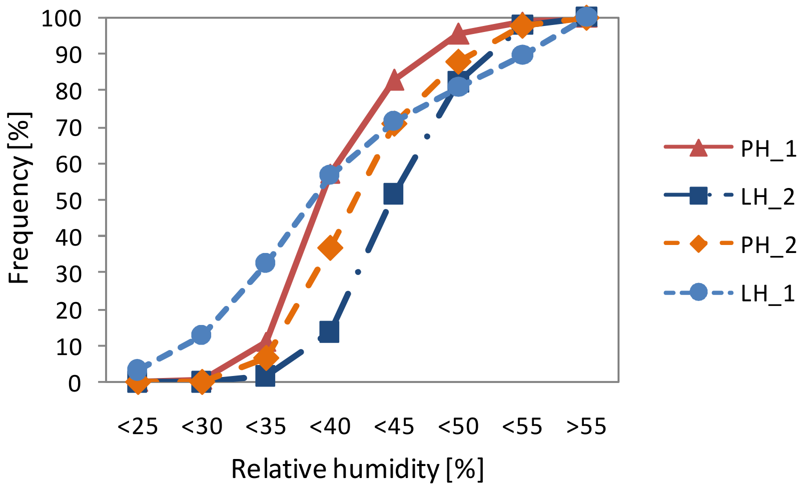


Figure 31. All apartments_SR_APR_R

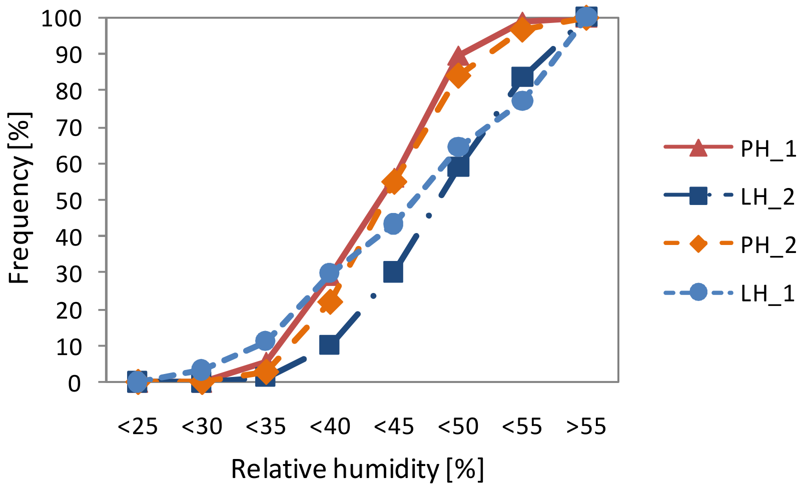


Figure 32. All apartments_SR_MAY_R

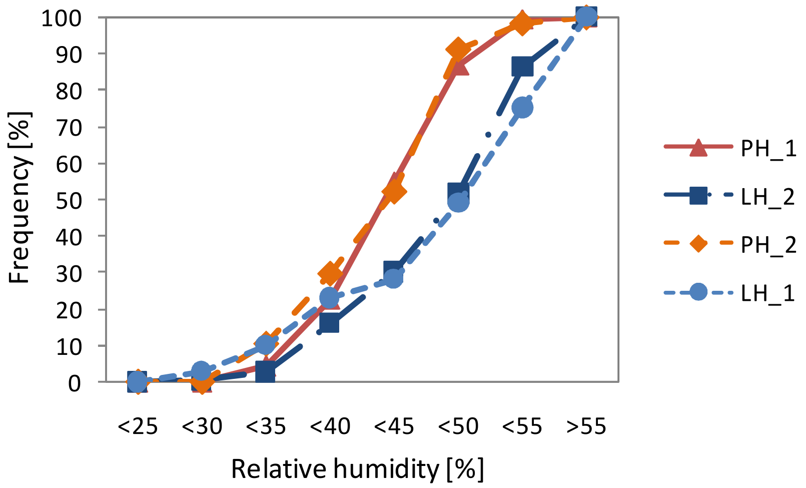


Figure 33. All apartments_SR_JUN_R

It can be revealed from Figure 29 to Figure 33 that in the sleeping room of PH_1 the relative humidity increases in the course of the measuring period starting from a rather low value in February (70% of the measured data was below a value of 35% relative humidity). LH_1 shows widely distributed values of relative humidity in April (more than 30% frequency for values below 35% RH and 10% frequency for values above 55% RH). The relative humidity values of LH_1 in May and June are less widely distributed and do not show high frequencies for values below 35%. The results for PH_2 and LH_2 are comparable and within a reasonable range over the whole observation period while the values in LH_2 are a slightly higher than the ones in PH_2 most of the time.

Therefore, it can be asserted that the relative humidity values are significantly lower in the single apartments of both houses during the colder period while in the warmer period the results for all sleeping rooms are comparable. However, the relative humidity values increase with rising outdoor temperatures.

The ventilation system probably affects the relative humidity in particular in winter; however very dry air can only be detected in single apartments. When using ventilation systems, people who live in single apartments might have problems with dry air.

In PH_1 and PH_2 the relative humidity values are more stable than in the low-energy apartments. Reason for this may be the controlled ventilation that provides the apartments with a constant air exchange.

In contrast to the beforehand shown results in the sleeping room, the relative humidity values in the living room (see appendix) are a bit different. One significant difference occurs in LH_1 which has very low relative humidity values in the living room. This situation may have resulted from the absence of the inhabitant during daytime. Figure 34 shows the relative humidity distribution of the living rooms in June.

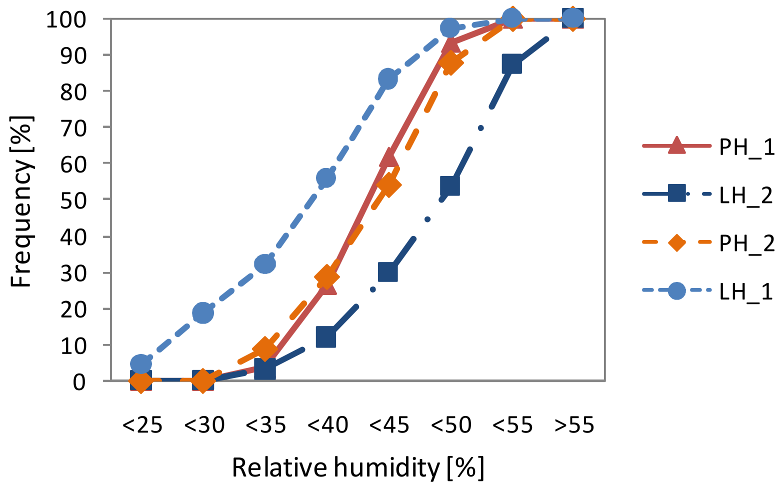


Figure 34. All apartments_LR_JUN_R

The following figures (Figure 35 - Figure 39) show the distribution of temperature frequencies in all living rooms of the apartments in the course of the observing period from February to June.

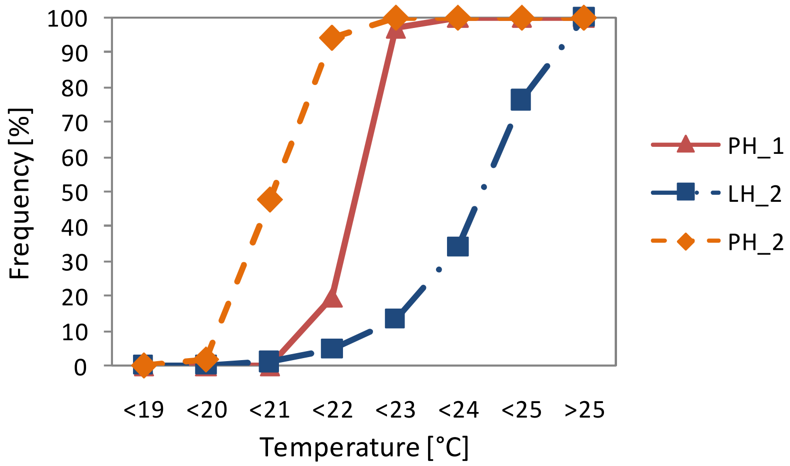


Figure 35. All apartments_LR_FEB_T

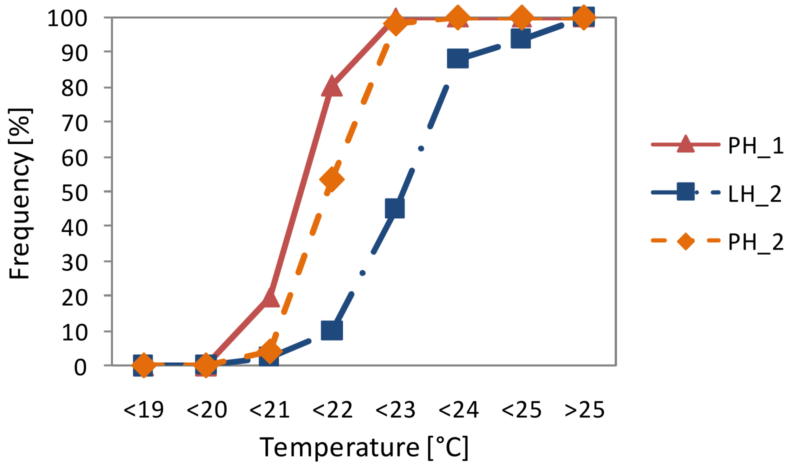


Figure 36. All apartments_LR_MAR_T

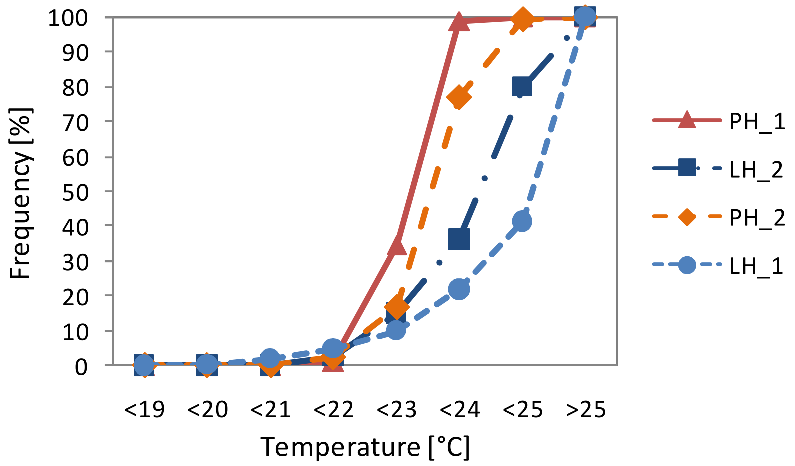


Figure 37. All apartments_LR_APR_T

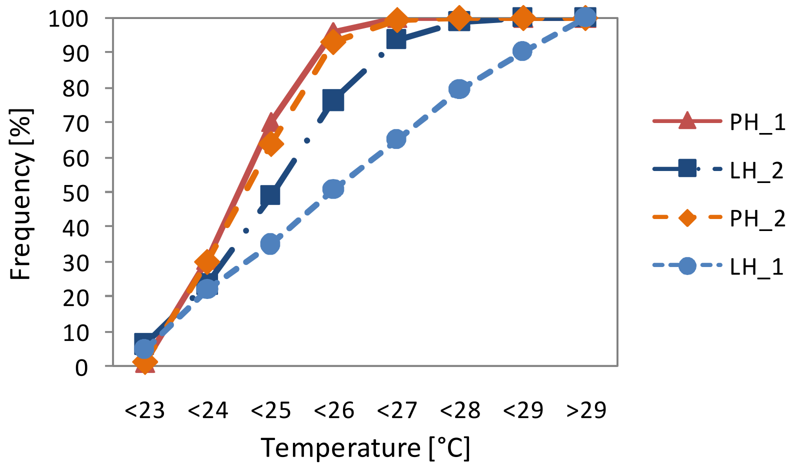


Figure 38. All apartments_LR_MAY_T

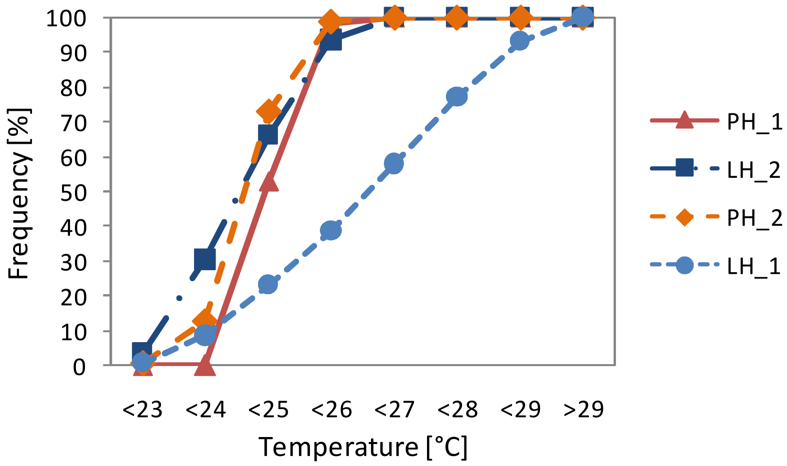


Figure 39. All apartments_LR_JUN_T

From Figure 35 to Figure 39 it can be revealed that the temperature distributions show a shift towards higher temperatures in the course of the observed time in each of the living rooms. (Please note the changes of the bins on the x axis from April to May.) In the living rooms of the passive house, the temperature is slightly lower in the winter months as well as in the summer months.

During the colder months, the temperature values in the observed living rooms are differing significantly. For instance in February the temperature values of PH_2 were lying between 20 and 21 degrees 50% of the time which is rather cool, while the temperature values in LH_2 were lying between 24 and 25 degrees about 30% of the time which is very warm. However, all these temperature values can be considered as within reasonable ranges.

In the warmer months, all apartments show comparable results for the temperature measurements except for LH_1. Figure 38 and Figure 39 show that the temperatures were significantly high in the living room of LH_1 in May and in June. However, as Figure 40 and Figure 41 show, the temperatures were considerably lower in the sleeping room of the same apartment although the sleeping room is oriented similarly and the shading behavior of the user was the same. The main difference between these two rooms is the size of the windows (in relation to the floor areas). Hence, it can be asserted that the main reason for the high temperatures in the living room in contrast to the sleeping room is the oversized window of the living room.

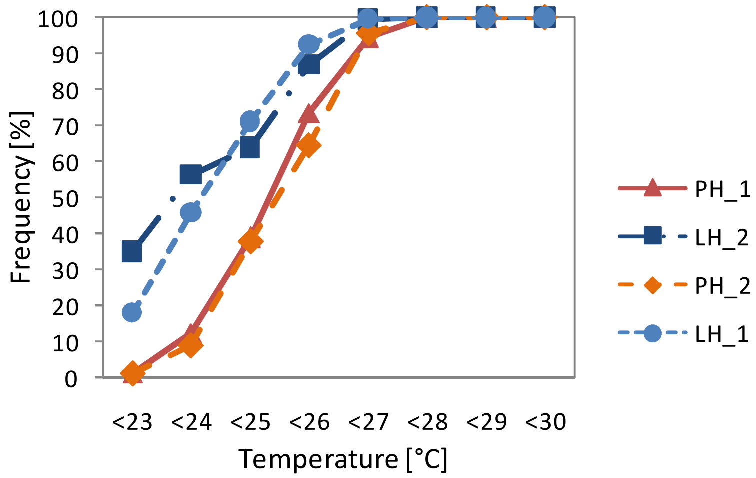


Figure 40. All apartments_SR_MAY_T

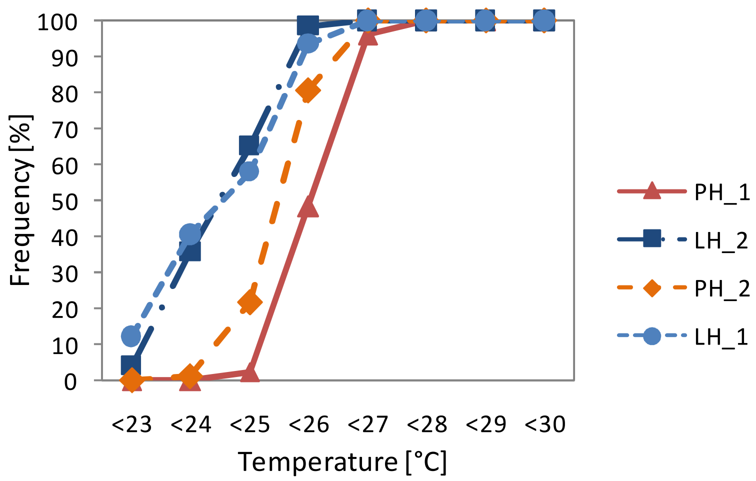


Figure 41. All apartments_SR_JUN_T

The shading behavior of the inhabitant who was absent during the day and could not shade the windows during this time may be a reason why the living room of LH_1 was overheated in contrast to the other living rooms with similar window sizes. Wagner (2008) implies that the LH had more overheated hours in summer 2008 than the PH which was influenced by the user behavior. The results of this work show comparable findings.

Figure 35 to Figure 39 show that the temperature values are more stable in the passive house apartments in particular during the colder period. This can be attributed to the use of the ventilation system that ensures constant ventilation with heated up air in daytime as well as during the night. In the warmer months, manual window ventilation is performed in both buildings, so the stability of the temperature values is comparable in all the living rooms, except for LH_1.

It can be revealed that the indoor environment with respect to overheating in summer is mainly influenced by the orientation of the rooms, user behavior and window areas.

3.2. Psychrometric charts

To assess the thermal comfort conditions inside the apartments, we calculated the fraction of time (in %), when measured indoor air temperature and relative humidity values were inside the comfort zone.

3.2.1. Overall comparison

Comparing the percentages of datapoints lying within the comfort zone over the entire monitoring period, the results in Table 9 can be revealed.

Table 9. Fraction of time within comfort zones (averages)

	PH 1	LH 1	PH 2	LH 2
Entire period	65.1%	-	60.6%	56.9%
April, May, June	82.3%	57.3%	78.4%	78.8%

As in February and March no data could be obtained for LH_1, two different sums were formed. The first one covers the whole monitoring period and the second one covers the period from April to end of June.

PH_1, PH_2 and LH_2 performed rather similarly in both categories. All of these three apartments performed even better in the warmer months. In contrast to that, LH_1 for which there is only a result for the warmer period, performed significantly worse. This finding is going to be analyzed in the following.

3.2.2. Detailed comparison

Having a more detailed look at the results, the reasons for the poor performance of LH_1 can be discovered. Table 10 summarizes the results (fraction of time within comfort zones) for individual months as well as the total monitoring period. Note that for these results different times of the day were considered depending on the room usage. The relevant times of the day for the living rooms was considered to be from 8:00 to 22:00, whereas the relevant times for the sleeping room was from 22:00 to 8:00.

Table 10. Fraction of time within comfort zones [%]

Month	Room	Apartment			
		PH_1	LH_1	PH_2	LH_2
February	SR	3.9	-	1.0	5.0
	LR	0.2	-	39.7	1.5
March	SR	62.2	-	21.6	67.4
	LR	91.0	-	73.2	22.5
April	SR	100.0	94.3	84.0	99.3
	LR	100.0	45.9	100.0	87.8
May	SR	60.9	64.8	41.6	61.7
	LR	81.7	40.3	77.6	58.2
June	SR	60.5	62.9	70.0	86.4
	LR	90.7	35.7	97.4	79.4
Entire period	SR, LR	65.1	-	60.6	56.9
April, May, June	SR, LR	82.3	57.3	78.4	78.8

Table 10 shows comparatively good results for the sleeping room of LH_1. However, the percentages of points within the comfort zone for the living room are significantly low. The following figures show the psychrometric charts including comfort zones and data points for the living room of LH_1 in April, May and June and explain the poor performance of this room.

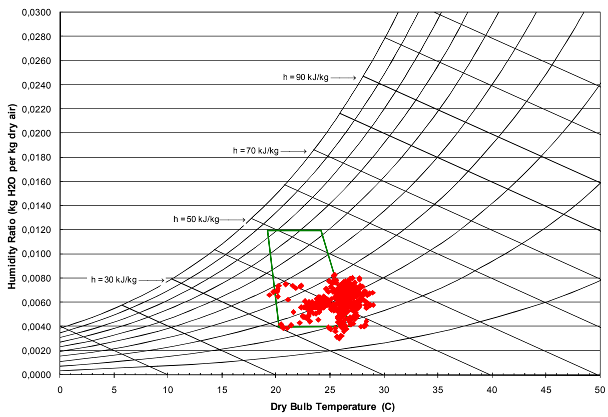


Figure 42. LH_1_LR_APR

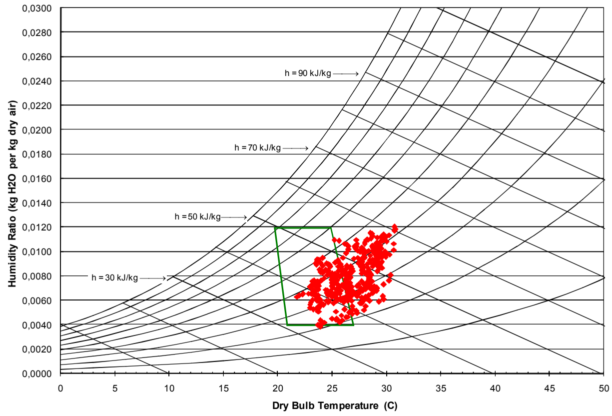


Figure 43. LH_1_LR_MAY

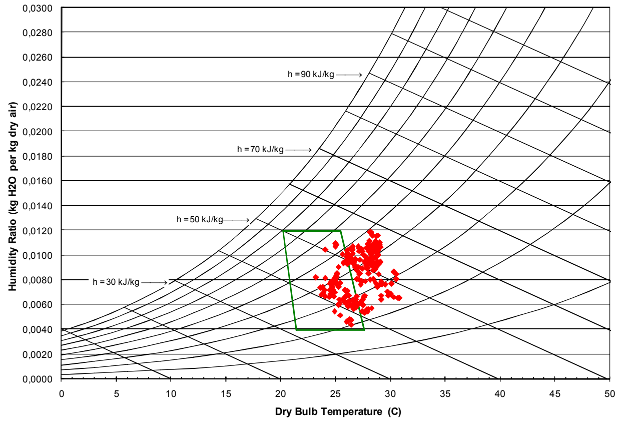


Figure 44. LH_1_LR_JUN

Figure 42 to Figure 44 display that the temperatures in the living room of LH_1 were very high during the monitored months. In May and in June the temperatures even rose above 30 degrees Celsius. This can be explained by the orientation, shading behavior and the window size. The window size turns out to be a major factor in particular when we compare temperatures in the sleeping and living rooms of LH_1 (Figure 44 and Figure 45), which have the same orientation and shading conditions. However, the living room window size (in relation to floor area) is significantly larger than that of the sleeping room. As Figure 7 shows, the temperature in the sleeping room of LH_1 does not rise above 27 ^{o}C in June. (Note that this difference prevails during both day and night).

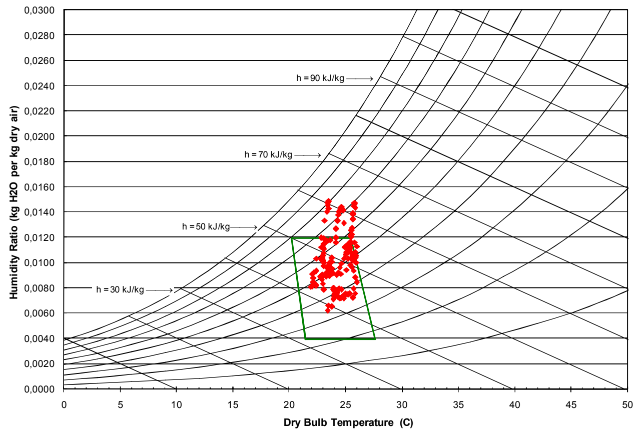


Figure 45. LH_1_SR_JUN

Table 10 also suggests a very low fraction of time in comfort zone for all apartments in February. The adaptive comfort theory suggests in this case comfort temperatures significantly lower than those maintained by the occupants as shown in Figure 46. The adaptive comfort zone only covers temperature values up to 21.5 degrees Celsius and as in all the apartments higher temperatures were maintained, it can be revealed that many people prefer higher temperatures than the adaptive comfort theory suggests for the winter months.

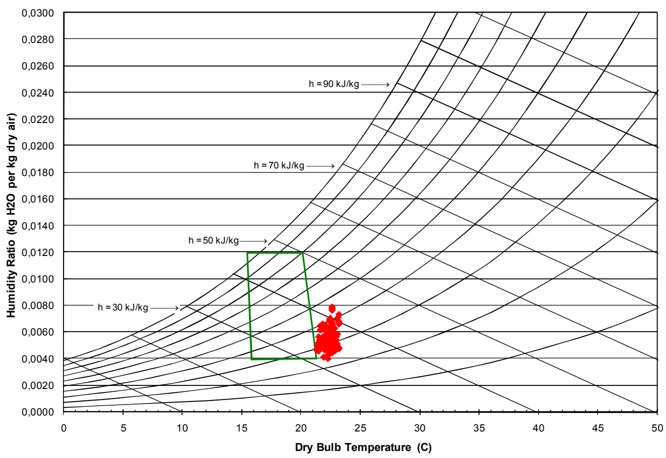


Figure 46. PH_1_LR_FEB

Generally, from the results for the thermal comfort calculations using the adaptive comfort zone theory it can be revealed, that both houses perform quite well with respect to the thermal comfort except for one room with a large window area and little shading that performed rather poor during the warmer months.

3.3. Predicted Mean Vote and Predicted Percentage of Dissatisfied

Calculating PMV (predicted mean vote) and PPD (predicted percentage of dissatisfied) is an alternative approach in assessing thermal comfort. The predicted mean vote shows people's feeling of thermal comfort on a scale from minus three to plus three. A negative value indicates that the person is cold while a positive value indicates that the person is hot. Values between -0.5 and 0.5 are considered comfortable. The predicted percentage of dissatisfied shows the percentage of people that are dissatisfied with the thermal situation.

3.3.1. Overall comparison

The following figures (Figure 47 - Figure 54) show the predicted mean votes for all the apartments over the entire monitoring period. PMV has been calculated for both the sleeping room and the living room.

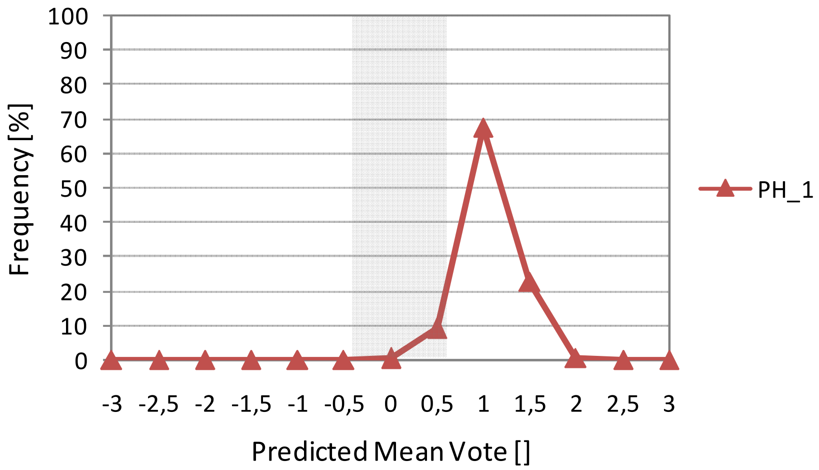


Figure 47. PH_1_SR_whole period

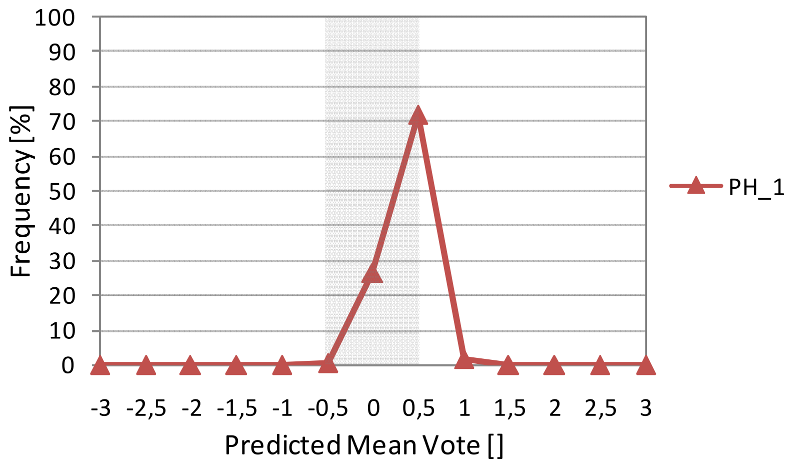


Figure 48. PH_1_LR_whole period

Figure 47 and Figure 48 show that PH_1 performs quite well over the entire period; however, the results for the living room are better than the results for the sleeping room. Nearly all of the data for the living room lies within a range of -0.5 to +0.5. In the sleeping room, the indoor air is apparently a little too warm.

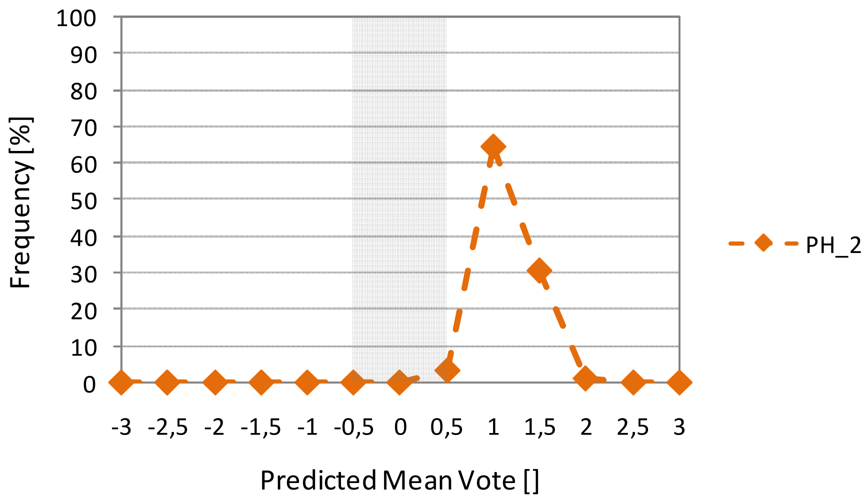


Figure 49. PH_2_SR_whole period

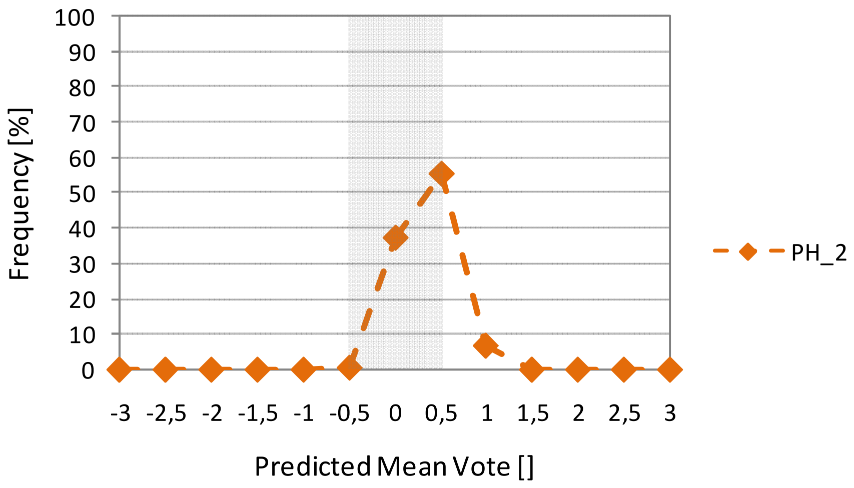


Figure 50. PH_2_LR_whole period

From Figure 49 and Figure 50 it can be revealed that PH_2 has rather similar results as PH_1. The living room performs very well. However, the temperature in the sleeping room is even slightly warmer than in PH_1. 30% of the monitored time, PMV lies around 1.5.

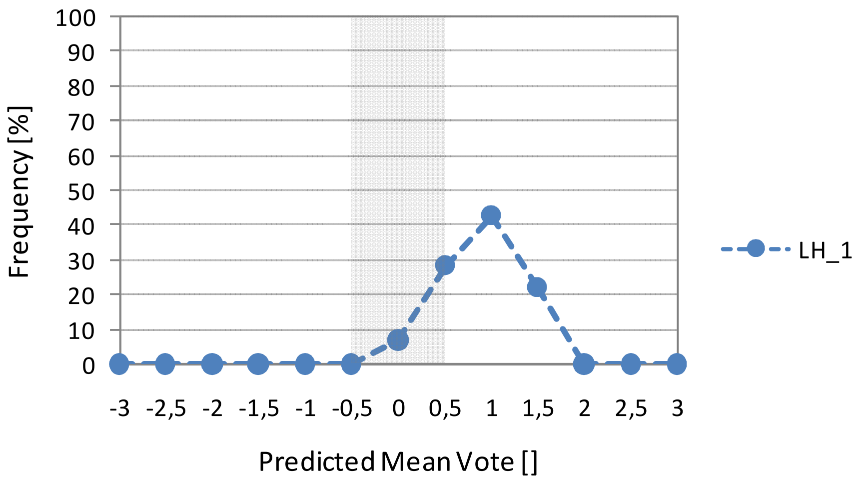


Figure 51. LH_1_SR_whole period

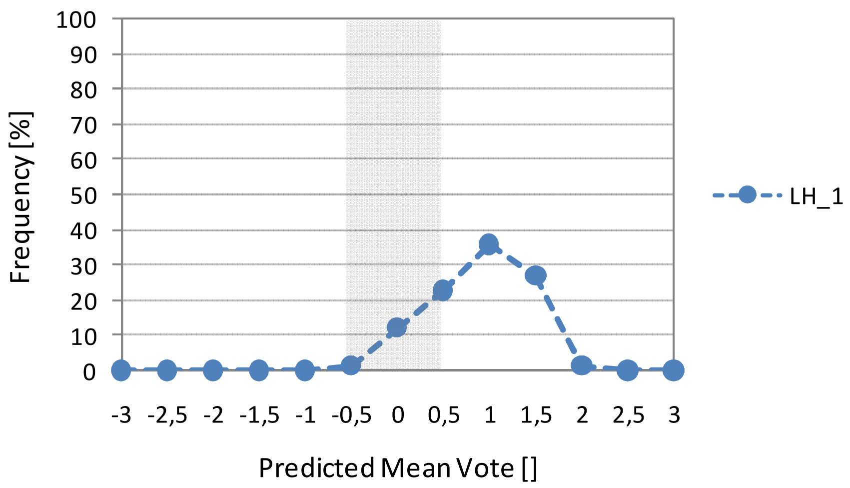


Figure 52. LH_1_LR_whole period

The thermal comfort of LH_1 with respect to PMV is not as good as in the comparable passive house apartment as can be asserted from Figure 51 and Figure 52. However, the sleeping room performs a bit better than the one of PH_1, it is still slightly too warm. The living room has significantly high PMV values. This result can also be found in the psychrometric charts.

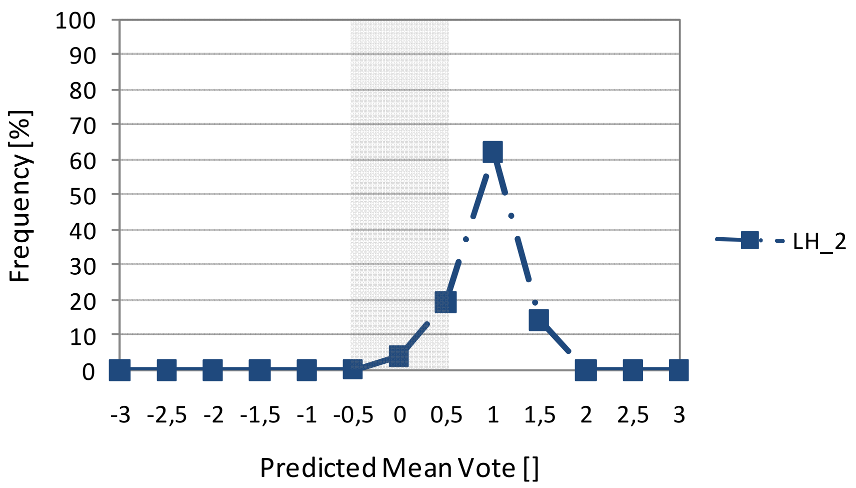


Figure 53. LH_2_SR_whole period

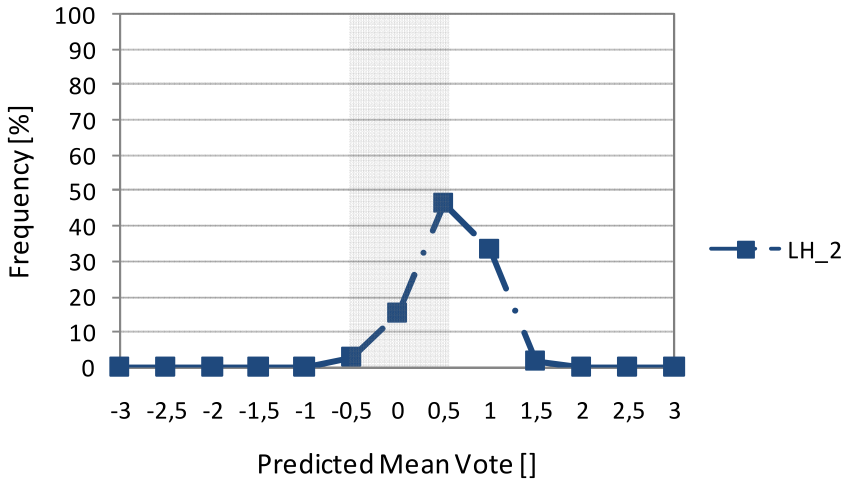


Figure 54. LH_2_LR_whole period

The results of LH_2 are comparable to the results of the passive house apartments as shown in Figure 53 and Figure 54. The living room performs a little better than the sleeping room. The predicted mean vote of the sleeping room is rather high.

The calculation of PMV shows that all the apartments perform quite well with respect to thermal comfort in the living rooms except for LH_1. In the living room of LH_1 the PMV values are too high during the whole monitored period. Reason for this is probably – like beforehand mentioned – the window area, orientation and shading behavior.

Too low temperatures have apparently never occurred in any of the apartments. All of the sleeping rooms tend to have high PMV values while most of the living rooms perform very well.

The high PMV values in the sleeping rooms can be attributed to the varying temperature demand of people. According to the results, the inhabitants of the monitored apartments prefer higher temperatures in the sleeping room than the healthy sleeping room temperature that is suggested by experts. It is rather difficult to find an appropriate indoor temperature for the sleeping room that is suitable for everybody. Onen et al. (1994) state that the temperature in the sleeping room should lie between 16 and 19 degrees Celsius. Therefore, these values were considered in the calculations. It is also possible that the actual clo-values maintained by inhabitants were lower than our assumptions. The people in the monitored apartments could have changed the temperatures at least in winter by opening the windows or turning down the heating but apparently they were satisfied with the relatively high sleeping room temperatures.

3.3.2. Detailed comparison

Having a more detailed look at the rather high PMV values in the sleeping room of PH_1 (Figure 55) it can be revealed that the predicted mean values are rather comparably high in all months of the observed period. The highest PMV values can be found in April, which is presumably because of higher temperatures than in February and March but still the same clo-values were used. The sleeping rooms of PH_2 and LH_1 perform about comparably (see appendix).

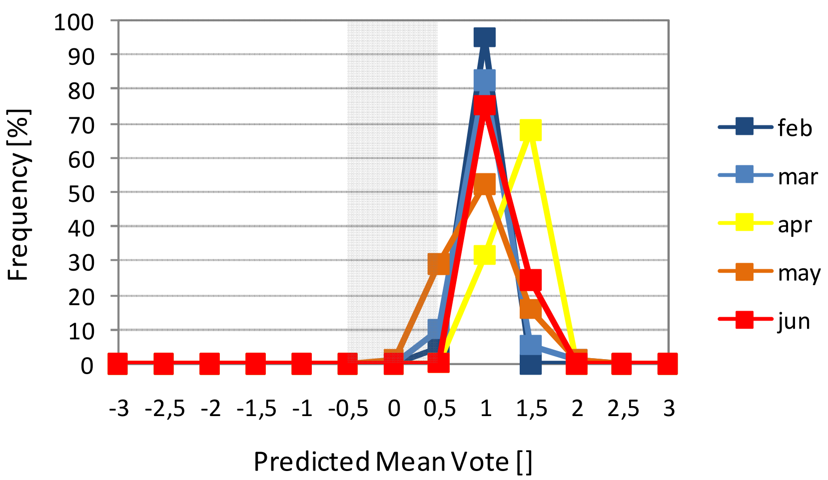


Figure 55. PH_1_SR_all months

The sleeping room of LH_2 performs a little better, in particular in the warmer months as can be revealed from Figure 56. The results for May and June lie partly within PMV values of -0.5 and +0.5. This outcome can be attributed to the orientation and window size of the sleeping room as well as the user behavior.

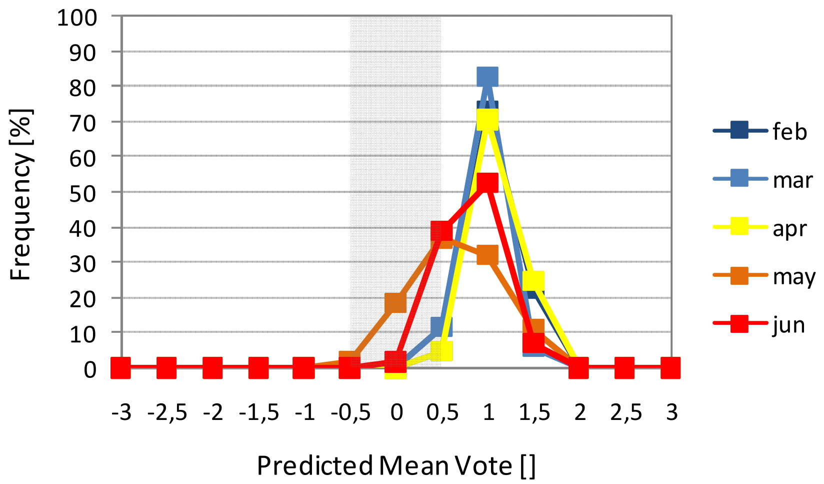


Figure 56. LH_2_SR_all months

In contrast to the performance of the sleeping room, the living room in PH_1 performs very well during all months of the whole monitored period as can be seen in Figure 57. Nearly all of the data lies between -0.5 and +0.5. The living rooms in PH_2 and LH_2 show comparable performances (see appendix).

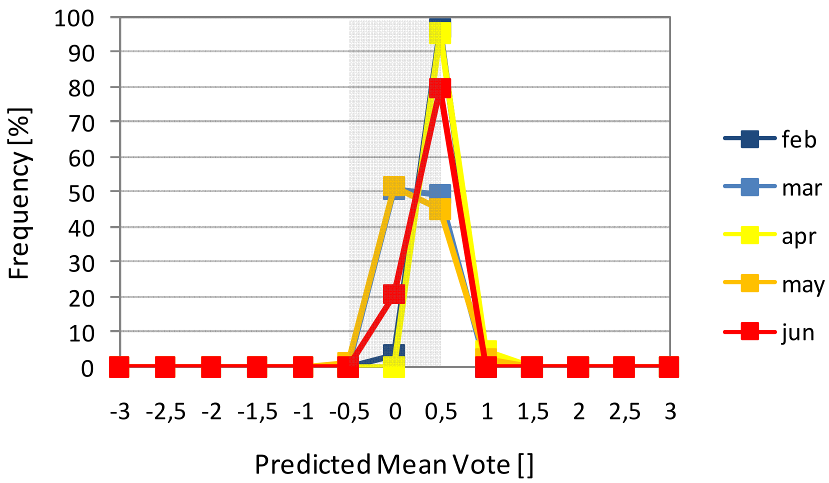


Figure 57. PH_1_LR_all months

From Figure 58 it can be asserted that LH_1 has significantly higher PMV values in the living room. The monthly differences are not considerable. The results occurred probably due to large window sizes, shading behavior and orientation of the room. However, the missing results for February and March would be interesting.

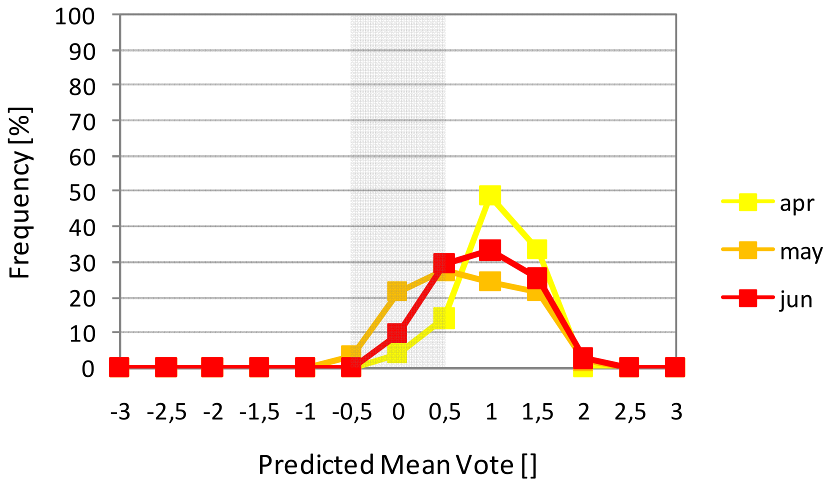


Figure 58. LH_1_LR_all months

3.3.3. Predicted Percentage of Dissatsfied

Table 11 shows the predicted percentages of dissatisfied (PPD) for each month and each room.

It implies that there is considerable difference between the results of the living room and the results of the sleeping room except for LH_1. LH_1 even shows better results in the sleeping room than in the living room.

Table 11. Predicted percentage of dissatisfied [%]

		Apartment			
Month	Room	PH 1	LH 1	PH 2	LH 2
February	SR	16.2	-	16.1	20.0
	LR	5.6	-	5.4	12.4
March	SR	17.5	-	22.0	16.8
	LR	5.3	-	5.5	8.2
April	SR	28.7	27.2	37.1	12.9
	LR	7.9	21.5	9.4	13.3
May	SR	17.4	11.8	20.8	11.0
	LR	6.4	17.4	6.5	9.3
June	SR	22.5	13.2	19.4	13.6
	LR	5.8	17.9	5.8	7.1
Entire period	SR, LR	**13.3**	**-**	**14.8**	**12.5**
April, May, June	SR, LR	**14.8**	**18.2**	**16.5**	**11.2**
Average	SR	20.5	17.4	23.1	14.9
Average	LR	6.2	18.9	6.5	10.1

In summary, PPD values in living rooms are fairly reasonable in all apartments, whereas sleeping rooms display higher PMV values except for LH_1 which can be attributed to window size, user behavior and orientation.

3.4. Evaluation by inhabitants

Selected inhabitants were asked to fill out a questionnaire comprising the chapters general information, evaluation of living room and sleeping room as well as evaluation of information to gain information about user satisfaction.

3.4.1. All Interviews

The interviews were analyzed statistically using standard deviation, mean values and averages. Given the small number of interviewees (five inhabitants of the passive house and six inhabitants of the low-energy house), the results are of limited representative value. Nonetheless, they do imply that the inhabitants in both building types are generally satisfied with indoor conditions.

The first diagram (Figure 59) shows the results for the following questions on a scale from +1(very poor) to +5(very good).

Q1: satisfaction with the heating system

Q2: satisfaction with the ventilation system

Q3: air quality in winter

Q4: air quality in summer

Q5: overall satisfaction with living in this building

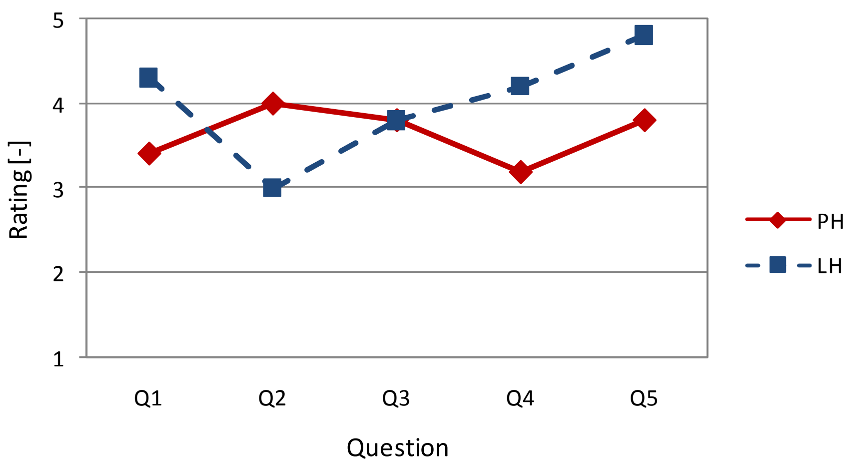


Figure 59. Both houses_Questions 1-5

The results for the questions Q1 to Q5 (Figure 59) imply that the residents of both houses are rather satisfied with heating, ventilation and air quality.

Q1 shows a higher acceptance of the heating system in the low-energy house while Q2 implies that the occupants of the passive house are very satisfied with the ventilation system. The ventilation system in the low-energy house finds medium acceptance. However, Figure 61 shows that the acceptance varies significantly between the interviewed people. The standard deviation for this question for the LH is 1.7.

On the one hand the residents of both houses are comfortable with the air quality in winter but on the other hand the passive house-inhabitants show only medium satisfaction with the air quality in summer. This can be attributed to high indoor air temperatures in the summer period that represents a problem for some residents, whereby the inhabitants of south-facing apartments are particularly affected. This topic is going to be further addressed in Q7.

The overall acceptance of the buildings is high for both houses but even higher in the low-energy house. The reason for this outcome is addressed in Figure 60 and Figure 61. The figures show that the overall acceptance is the passive house (Q5) is very high except for one interviewed person. This is implied by the whiskers of the boxplots. The standard deviation for Q5 is 0.3 in the LH and 1.1 in the PH.

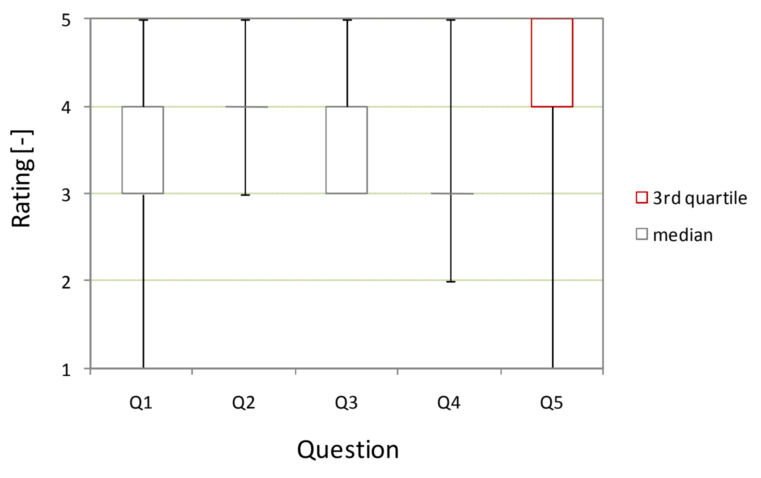


Figure 60. Boxplots Question 1-5 PH

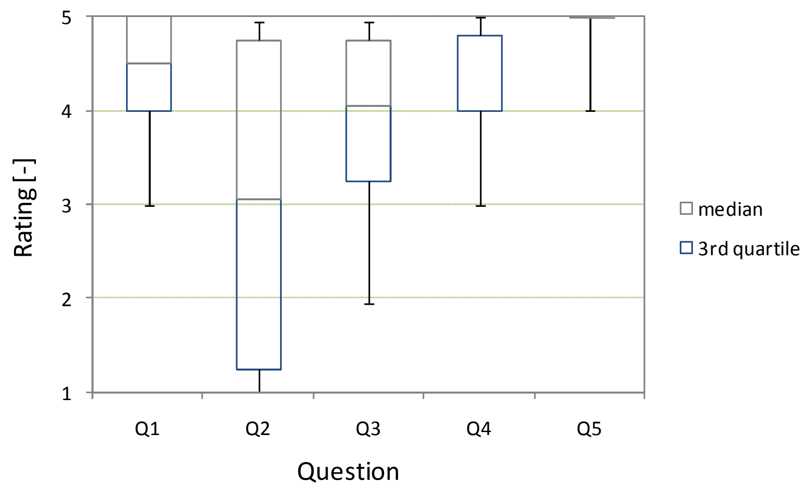


Figure 61. Boxplots Questions 1-5 LH

Figure 62 shows the results for question Q6 to question Q9 on a scale from +2(very hot/humid) to -2(very cold/dry).

Q6: temperature in winter

Q7: temperature in summer

Q8: relative humidity in winter

Q9: relative humidity in summer

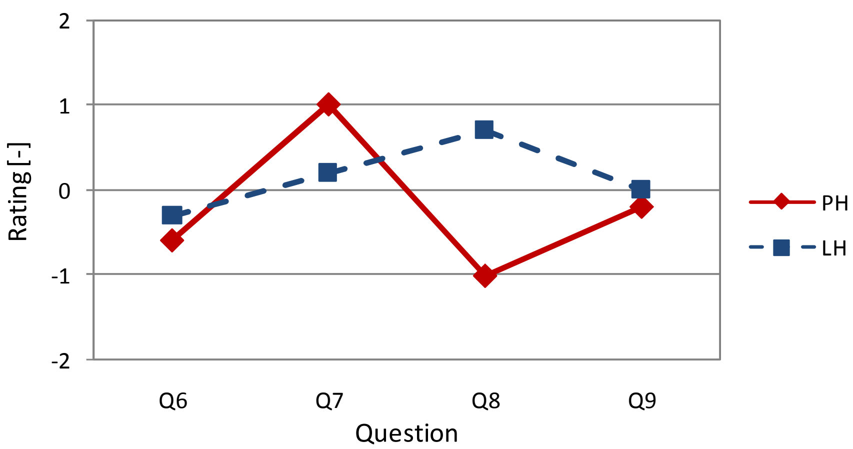


Figure 62. Both houses_Questions 6-9

The temperatures in winter are considered as around neutral in both buildings as Figure 62 suggests. However the temperatures in summer are considered as being too warm in the passive house which explains the result of Q4. The interviewed probands from the passive house are presumably living in south-facing apartments.

While the relative humidity in summer is considered as neutral in both buildings, the results for the relative humidity in winter are evaluated as significantly differing. On the one hand the occupants of the passive house consider the air as too dry and on the other hand the residents of the low-energy house consider it as too humid. Results that support the users' impression about the humidity in winter can be found in the chapter showing histograms for relative humidity.

The standard deviation for each question from Q6 to Q9 lies below 0.9 in both buildings. This implies that the results were not varying significantly.

Figure 63 shows the results for Q10 to Q14 for both houses.

Q10: satisfaction with HVAC support

Q11: personal behavior affects energy consumption

Q12: personal behavior is influenced by possible consequences on energy consumption

Q13: feel informed about heating system

Q14: feel informed about ventilation system

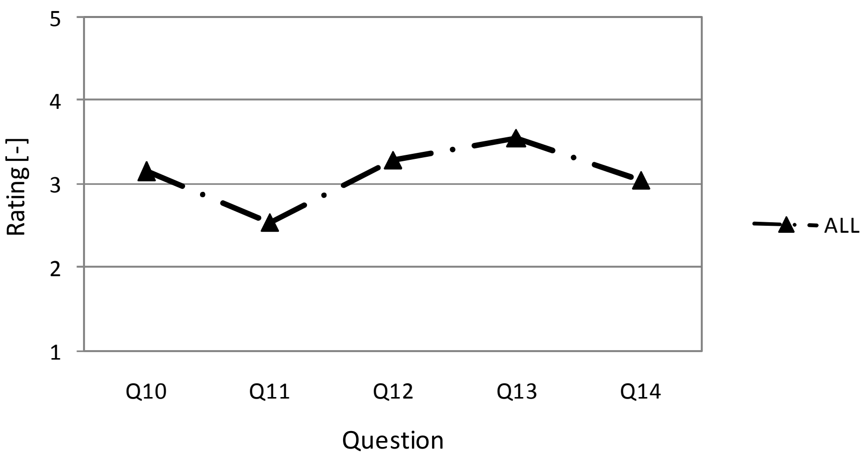


Figure 63. All interviews_Question 10-14

From Figure 63 it can be asserted that the inhabitants of both buildings are fairly satisfied with the HVAC support. The interviewed people are not sure if they can influence the energy consumption with their personal behavior but apparently most of them try to take the possible consequences of their actions into account. They feel a bit better informed about the heating system than they do about the ventilation system.

3.4.2. Inhabitants of monitored apartments

This chapter shows a more detailed evaluation for the monitored apartments which addresses the questions of the interviews that were not included in the previous chapter. As these are only 4 interviewed residents, the results are presented verbally without using any statistical methods.

The residents of the monitored low-energy apartments were very satisfied with the lighting situation, so were the residents of the passive house.
None of the inhabitants is disturbed by noise from the ventilation system. However some of the LH occupants complained about traffic noise which can be explained by the position of the low energy house on the site.

The regulation of the ventilation system in the PH finds medium acceptance. The occupants of the LH perform window ventilation more often than the residents of the PH, in particular in winter, the difference is significant.

Some of the inhabitants of both buildings complained about not being able to use the shading when they leave the apartment because the shading can only be used up to a certain amount of wind velocity.

During the week LH_1 is only occupied in the evening and at night while all the other apartments are occupied during the day as well as during the night. That may explain the high temperatures in summer in the living room that only occurred in LH_1 where the inhabitant could not shade during daytime because he was absent.

None of the interviewed persons showed symptoms that could be associated with the sick building syndrome.

3.5. Energy Consumption and Building Costs

Little energy consumption because of ecological and economical reasons is the major reason for building energy-efficient houses. This chapter gives an insight to the actual energy consumption of the houses in this case study.

Energy-efficient buildings are more expensive than ordinary buildings with respect to the initial building costs, but consume less energy during the operating time. Rising costs for energy can make these buildings even more cost-efficient in the future.

3.5.1. Energy Consumption

The energy consumption comprises the energy used for heating and the electrical energy. The consumption of energy for heating is lower in the passive house because it is better insulated and loses less heat due to ventilation. On the other hand, the general (not taking the apartments into account) consumption of electrical energy is higher in the passive house due to the energy-demands of the ventilation system.

As for 2009 there is no complete data available yet, this is the energy consumption for heating in 2008.

Table 12. Energy consumption for heating, 2008 [kWh]

		Apartment			
Type of energy	Unit	PH_1	PH_2	LH_1	LH_2
Heating	[kWh]	498.9	1358.7	1153.8	3922.2
	[kWh.m^{-2}]	8.4	15.2	22.4	46.4

From Table 12 it can be revealed that the comparable passive house apartments consumed about one third of the amount of energy for heating from the comparable low energy house apartments.

Considering the electrical energy consumption, the consumption comprises on the one hand the general consumption of each house and on the other hand the consumption of each apartment.

At first, the apartment component of the electrical energy consumption is addressed. From Table 13 it can be revealed that the consumption of electrical energy in the monitored passive house apartments is significantly lower than in the monitored low-energy apartments. In contrast to that, when comparing the consumption of electrical energy of other apartments of both buildings, the values differ only marginally. So, it can be revealed that the lower electrical energy consumption of the monitored passive house apartments may be a result of user behavior.

Secondly, the general component of the electrical energy consumption is addressed (this is the general consumption of the entire building). It is higher in the passive house as shown in Table 13. This can be attributed to the ventilation system which consumes 33.11 kWh a day (Spoerk-Duer, 2009) which leads to an annual consumption of about 12 000 kWh.

The table also shows the total consumption of electrical energy per m^2, comprising the apartment component and the general component. The comparable passive house apartments have a lower consumption of electrical energy than the low-energy apartments.

Table 13. Electrical energy consumption, 2008 [kWh]

		Apartment			
Type of energy	Unit	PH_1	PH_2	LH_1	LH_2
Electrical (apartment component)	[kWh]	669.4	2085	1388.8	4281.3
	[$kWh.m^{-2}$]	11.28	23.30	26.94	50.67
Electrical (general component, entire block)	[kWh]	22786.3		7441.4	
	[$kWh.m^{-2}$]	9.48		3.18	
Electrical (apartment plus general component)	[$kWh.m^{-2}$]	20.76	32.78	30.12	53.85

Considering all these results, the passive house has a significantly lower energy consumption than the low-energy house.

In Table 14 the calculation of the CO_2 emissions for the monitored apartments is shown. The calculations were performed using a calculator provided by IWR (2009). It can be asserted that the passive house apartments produce significantly less CO_2 emissions than the low-energy house, however in contrast to an ordinary building both perform very well.

Table 14. CO_2 Emissions [kg], 2008

	PH_1	PH_2	LH_1	LH_2
Heating	112	306	260	882
Electrical Energy	728	1731	916	2685
Total	840	2037	1176	3567

It has to be mentioned that both houses are heated by a local district heating network which produces less CO_2 emissions than other heating systems. Therefore, the difference between the houses with respect to CO_2 emissions would be even higher using a different heating system.

Another aspect of energy consumption is the embodied energy of a building. Embodied energy is the energy that was used during the production process of a product including raw material extraction, transport, manufacture and deconstruction. As the passive house is equipped with additional insulation, better windows and a ventilation system, it has more embodied energy than the low-energy house. We estimated the additional embodied energy and initial CO_2 emissions. We used the assumptions for embodied energy and CO_2 emissions of the insulation from the GEMIS database (Schuss, 2004) and of the windows and ventilation system from "Ökologischer Bauteilkatalog" (1999). Table 15 shows that the additional embodied energy of the passive house is 68.8 kWh/m^2 whereas the additional CO_2 emissions are 30.5 kg/m^2.

Table 15. Additional embodied energy and CO_2 emissions of the passive house

	Embodied energy [kWh/m^2]	CO_2 emissions [kg/m^2]
Insulation	47.7	25.7
Windows	6.1	1.6
Vent. System	15.0	3.2
Total	68.8	30.5

As shown in Table 16, the amortization of the passive house apartments with respect to embodied energy and total energy consumption during operation time occurs after 2.9 years in the case of the single apartment and 1.3 years in the case of the larger apartment. Considering the CO_2 emissions, the amortization process of the passive house apartments takes 5.4 years for the single apartment and 1.8 years for the larger apartment.

Table 16. Amortization of embodied energy and CO_2 emissions

	Energy	CO_2	Energy	CO_2
Apartment	PH_1 vs LH_1		PH_2 vs LH_2	
Annual reduction	23.4 kWh/m^2	5.7 kg/m^2	52.3 kWh/m^2	17.1 kg/m^2
Additional initial	68.8 kWh/m^2	30.5 kg/m^2	68.8 kWh/m^2	30.5 kg/m^2
Amortization [years]	2.9	5.4	1.3	1.8

3.5.2. Building Costs

The initial costs for building a passive house are higher than the costs for building a low-energy house.

From Table 17 it can be asserted that in this case, the additional costs for building a passive house were 4.69%.

Table 17. Additional building costs (Schoeberl, 2009b)

Bauteil	Mehrkosten /m² Bauteil	Mehrkosten /m² WNF	Einheit	Mehrkosten % der Baukosten
8.1 Außenwand	+25,50	+11,36	Euro/m²	+1,02%
8.2 Dach				
8.2.1 Dachfläche	+56,05	+7,96	Euro/m²	+0,72%
8.2.2 Dachterrassen	+58,62	+7,58	Euro/m²	+0,68%
8.3 Unterste Geschossdecke	+27,00	+6,45	Euro/m²	+0,58%
8.4 KG Zugang Stiegenhaus	+1.745/Stk	+4,08	Euro/m²	+0,37%
8.5 Wände über Tiefgarage	+8,78	+0,35	Euro/m²	+0,03%
8.6 Fenster	+76,15	+16,55	Euro/m²	+1,49%
8.7 Hauseingang	+250/Stk	+0,21	Euro/m²	+0,02%
8.8 Notkamin	-6.125/Stk	-2,78	Euro/m²	-0,25%
8.9 Verschattung	0,00	0,00	Euro/m²	0,00%
8.10 Luftdichtheit				
8.10.1 Aufzug	0,00	0,00	Euro/m²	0,00%
8.10.2 Elektroinstallationen	0,00	0,00	Euro/m²	0,00%
8.10.3 Sanitärinstallationen	0,00	0,00	Euro/m²	0,00%
8.11 Lüftungsanlage				
8.11.1 Mehrkosten	+135.500/Stk	+56,20	Euro/m²	+5,06%
8.11.2 Minderkosten	-36.502/Stk	-15,14	Euro/m²	-1,36%
8.12. Heizung				
8.12.1 Mehrkosten	0,00	0,00	Euro/m²	0,00%
8.12.2 Minderkosten	-91.618,00/Stk	-38,00	Euro/m²	-3,42%
Zwischensumme Minderkosten		-55,92	Euro/m²	-5,03%
Zwischensumme Mehrkosten		+110,74	Euro/m²	+9,97%
Summe Mehrkosten		**+54,82**	**Euro/m²**	**+4,94%**
Skonto und baukostenmindernde Abzüge	5 %	-2,74	Euro/m²	-0,25%
Gesamtsumme Mehrkosten		**+52,08**	**Euro/m²**	**+4,69%**

The table also shows that the major factors for the additional costs are the ventilation system, the windows and the costs for the additional insulation in particular the insulation for the exterior walls. The ventilation system is the most important factor in this calculation.

We tried to estimate an amortization period that shows in what period of time the costs for the passive and the low-energy building will even when additional initial costs for the passive house and additional operating costs for the low-energy house are considered. We obtained our assumptions for the energy costs from IWO Austria (2010) and Wien Energie (2010). Table 18 shows the results of this estimation. When comparing PH_1 with LH_1, it takes 17.8 years to reach even costs while when PH_2 is compared to LH_2 it takes only 7.9 years for amortization. Please note, that this is a simple payback analysis, not considering for example rising energy costs that may accelerate the amortization process in the future. Apart from that, the use of different types of energy (other than district heating) can also shorten the amortization period.

Table 18. Cost amortization

	Unit	PH_1	PH_2	LH_1	LH_2
District heating	[kWh/m2]	8.40	15.20	22.40	46.40
Electrical Energy	[kWh/m2]	20.76	32.78	30.12	53.85
Costs District heating	[€/m2]	0.78	1.42	2.09	4.32
Costs Electrical Energy	[€/m2]	3.60	5.69	5.23	9.35
Total Energy Costs	[€/m2]	4.39	7.11	7.32	13.67
Additional initial costs	[€/m2]	52.08	52.08		
Less Energy costs	[€/m2/year]	2.93	6.57		
Amortization	[years]	17.8	7.9		

4. CONCLUSION

4.1. Main contribution

A comparison of passive house apartments with low energy apartments in Vienna was conducted based on monitored indoor environmental conditions, user evaluation, metered energy use, calculated CO_2 emissions, and construction costs data.

The evaluation of the indoor environmental performance of these two buildings is based on empirical data that was collected over a period of five months. A database with more than 500.000 data points was collected. Thus, an objective assessment of the indoor environmental conditions in the buildings is possible.

The results suggest that both passive and low-energy apartments performed well in view of thermal conditions and indoor air quality, even though the performance of passive apartments was slightly better. Influences of the ventilation system of the passive house on indoor air quality were detected. From this work it can be asserted that the use of a ventilation system has positive effects on carbon dioxide concentrations in particular during cold periods and especially in densely occupied apartments.

The inhabitants of both buildings turned out to be satisfied with indoor conditions and building systems.

Passive house apartments were shown to consume approximately 65% less heating energy and 35% less electrical energy as compared to low-energy apartments. Moreover, passive apartments' CO_2 emissions (calculated based on metered operation energy usage) was approximately 25 to 40% less than low-energy houses. Considering embodied energy and CO_2 emissions of building parts, the amortization of the embodied energy takes 1.3 to 2.9 years whereas the amortization of the CO_2 emissions takes 1.8 to 5.4 years. The initial costs penalty associated with the construction of passive apartments was (compared to low-energy apartments) 5%. Using a simple payback analysis, the amortization process would take 7.9 to 17.8 years. Rising energy costs are not considered in this calculation.

4.2. Future research

Future efforts should definitely focus on larger studies with more apartments and measurements over a longer period of time.

A number of at least five apartments in each building would be reasonable. Moreover, the orientation of the various apartments should be similar and the number of inhabitants should be the same, like it was shown in this work. That is crucial because otherwise the situations cannot be compared because of too many parameters that have to be taken into account.

It would be helpful to have data over a period of two years to be able to compare the annual changes and, most important when assessing a ventilation system, the changes between seasons. In this work, only one month which was measured was very cold, in future studies there should definitely be a more monitored winter months.

An interesting aspect that should be scrutinized in future efforts is the difference of indoor surface temperature of the exterior building elements between a passive house and a low energy house. Schoeberl et al. (2009a) claim that the surface temperatures of exterior building elements in passive houses are similar to the temperatures of the interior building elements in contrast to historic buildings due to insulation. It would be interesting to monitor the surface temperatures in both buildings.

Apart from that, a more elaborate cost amortization calculation would be helpful in assessing such buildings.

5. References

5.1. Literature

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5.2. Tables

5.3. Figures

The floor plans of the apartments (Figures 5, 6, 9 and 10) are based on plans provided by Architekt Guenter Lautner.

Figures 3 and 4: Announcement 2009, map reproduced based on public display at buildings' location.

ACKNOWLEGEMENTS

First, I would like to thank my advisor Prof. Ardeshir Mahdavi whose constant support and helpful suggestions made this thesis possible.

My thanks also go to the members of the Department of Building Physics and Building Ecology who helped me with many questions.

Furthermore, I would like to thank BUWOG GesmbH, Schoeberl & Poell GmbH and Architekt Guenter Lautner for providing me with information and in particular AEE Intec who provided equipment and help for this work.

Above all I want to thank my parents, my brother and friends who always supported and encouraged me.

6. APPENDIX

6.1. Further results

In the following figures (Figure A 1 - Figure A 47), further results are shown.

6.1.1. All apartments

CO2

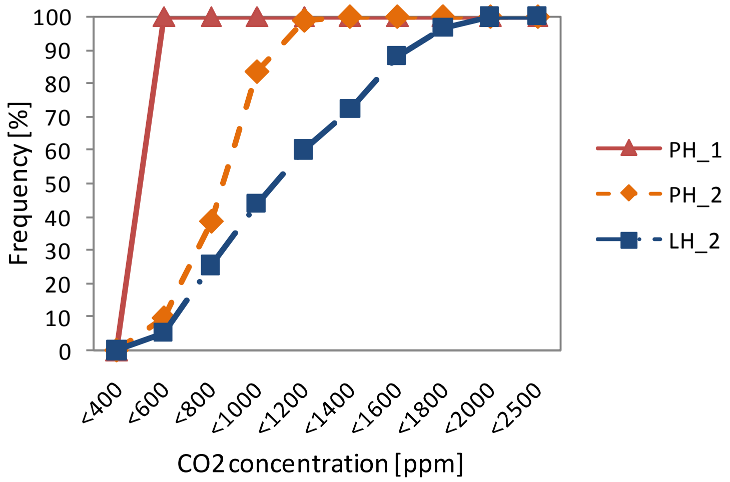

Figure A 1. All apartments_LR_FEB_C

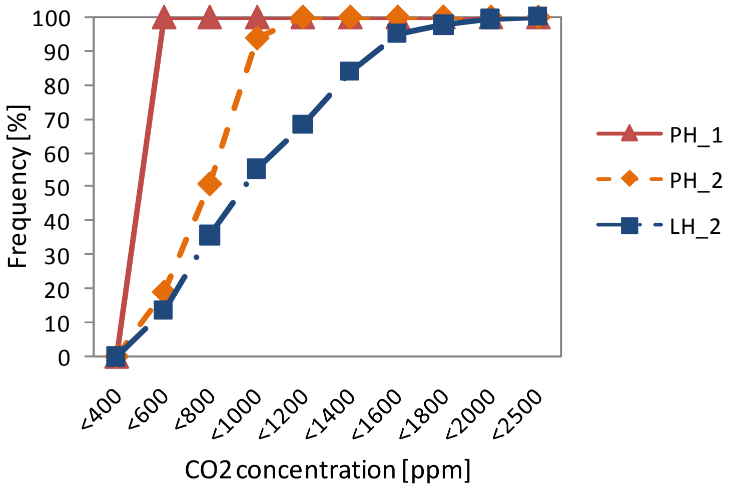

Figure A 2. All apartments_LR_MAR_C

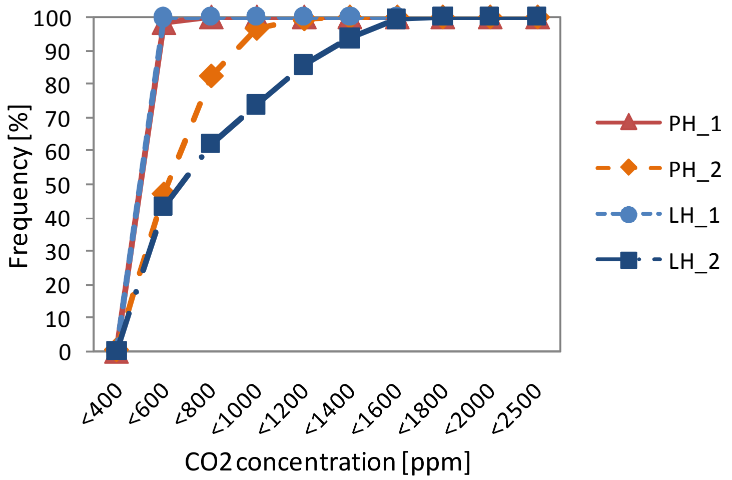

Figure A 3. All apartments_LR_APR_C

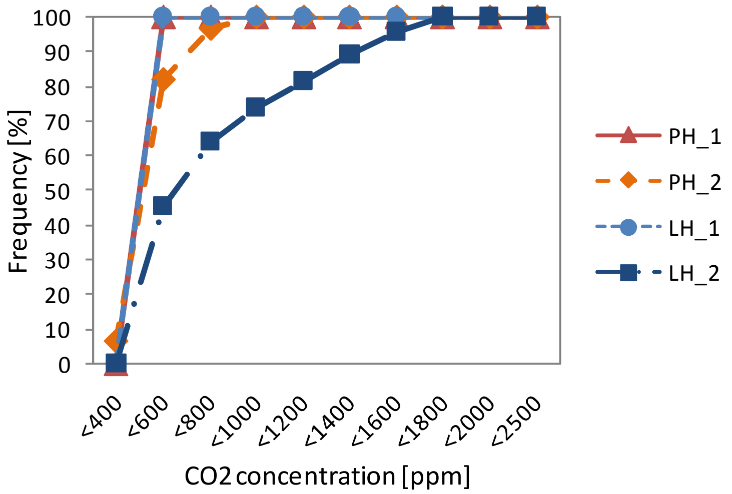

Figure A 4. All apartments_LR_MAY_C

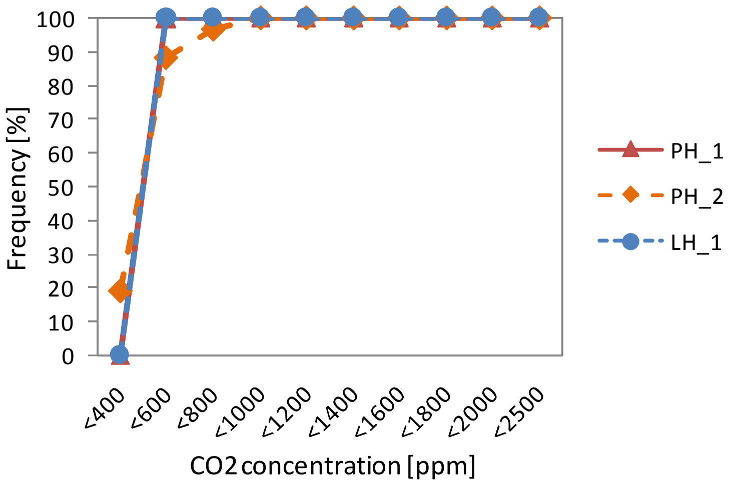

Figure A 5. All apartments_LR_JUN_C

RELATIVE HUMIDITY

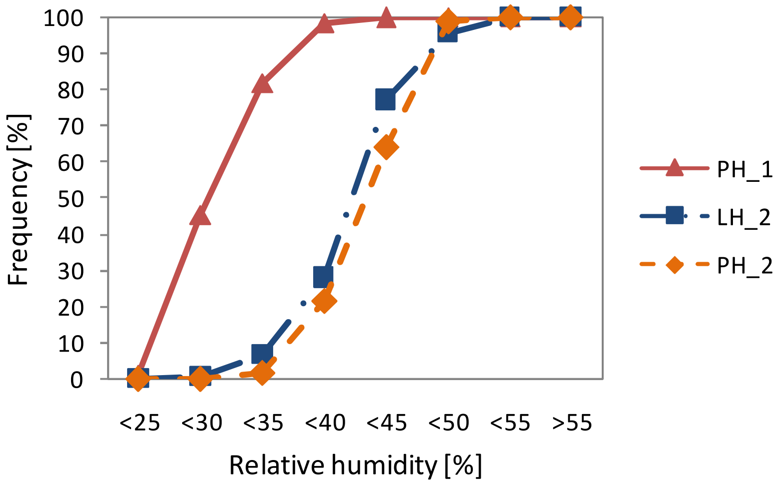

Figure A 6. All apartments_LR_FEB_R

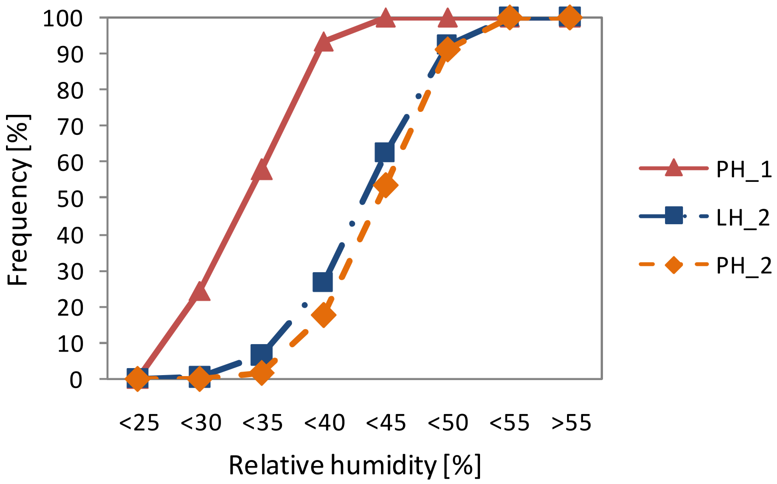

Figure A 7. All apartments_LR_MAR_R

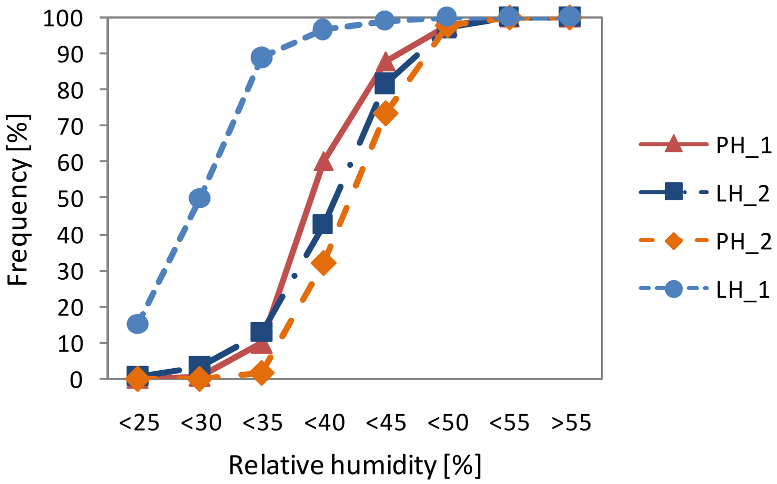

Figure A 8. All apartments_LR_APR_R

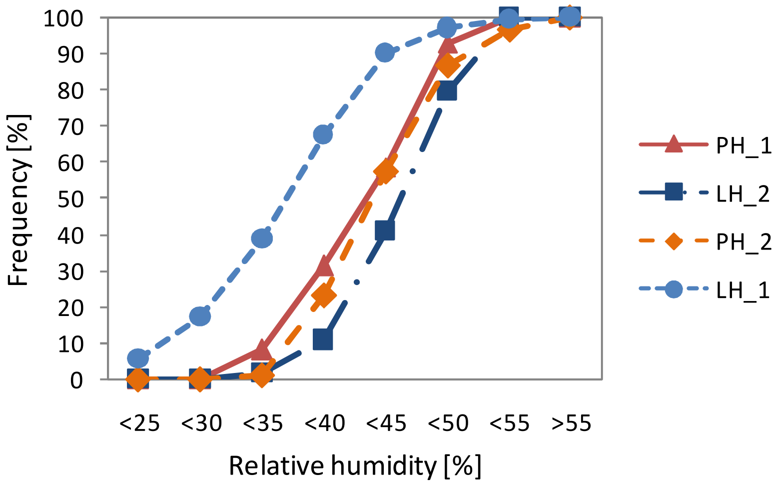

Figure A 9. All apartments_LR_MAY_R

TEMPERATURE

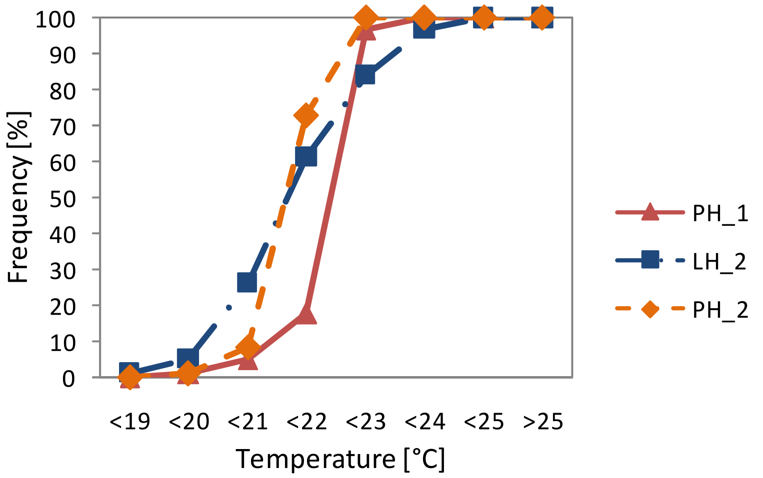

Figure A 10. All apartments_SR_FEB_T

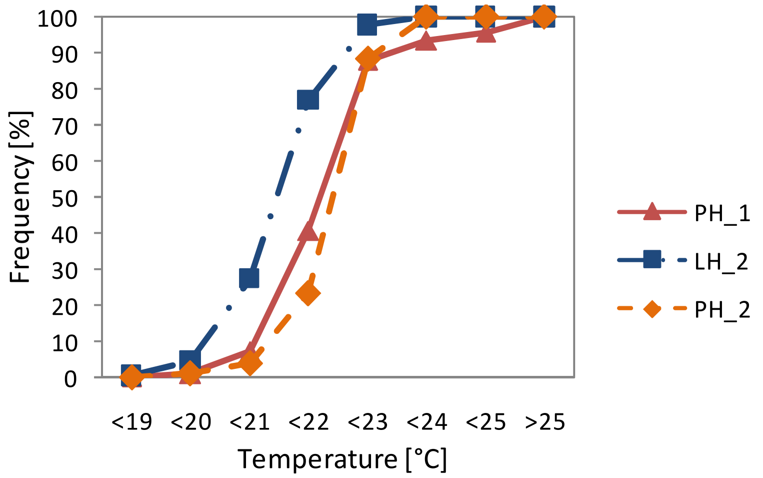

Figure A 11. All apartments_SR_MAR_T

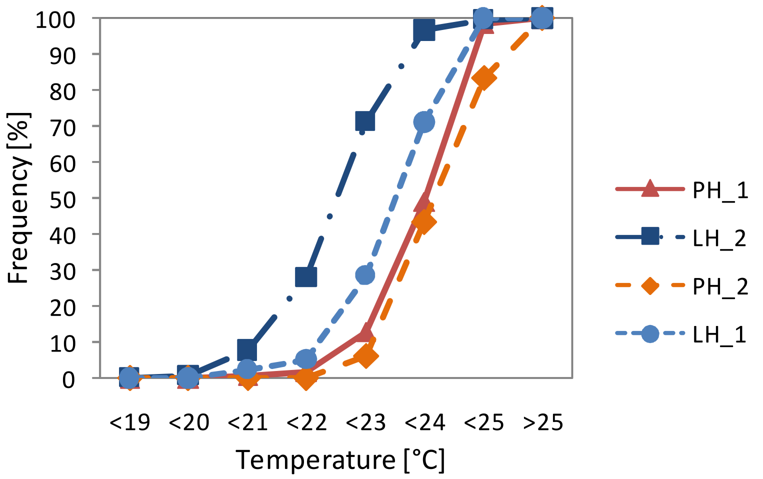

Figure A 12. All apartments_SR_APR_T

6.1.2. Passive house apartment 1

PSYCHROMETRIC CHARTS

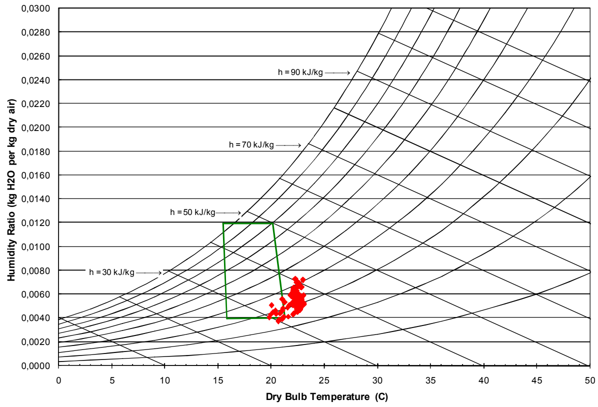

Figure A 13. PH_1_SR_FEB

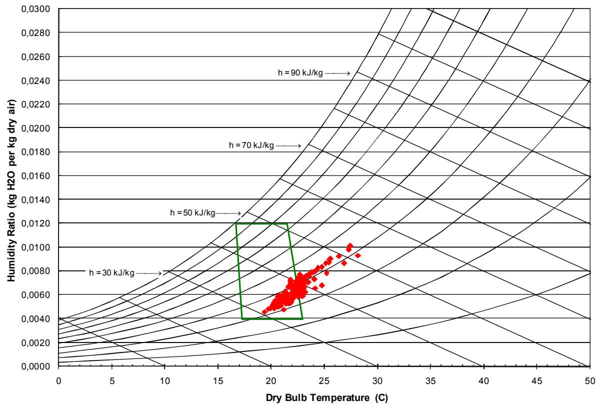

Figure A 14. PH_1_SR_MAR

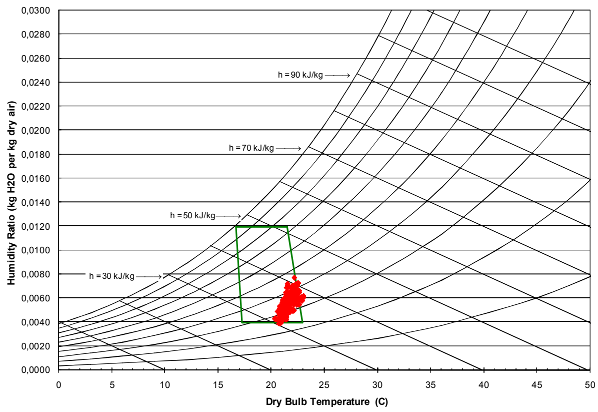

Figure A 15. PH_1_LR_MAR

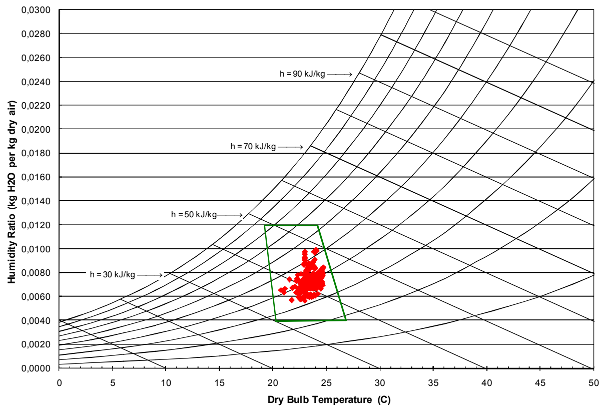

Figure A 16. PH_1_SR_APR

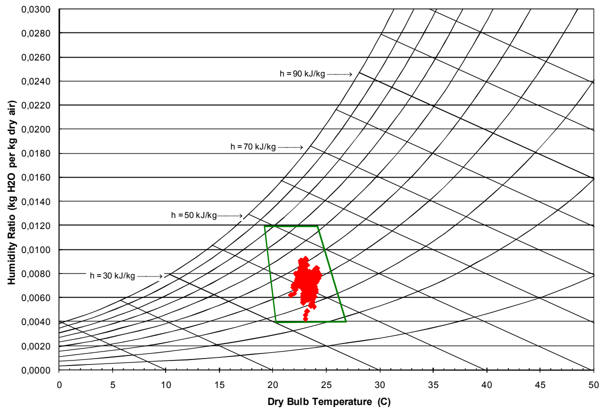

Figure A 17. PH_1_LR_APR

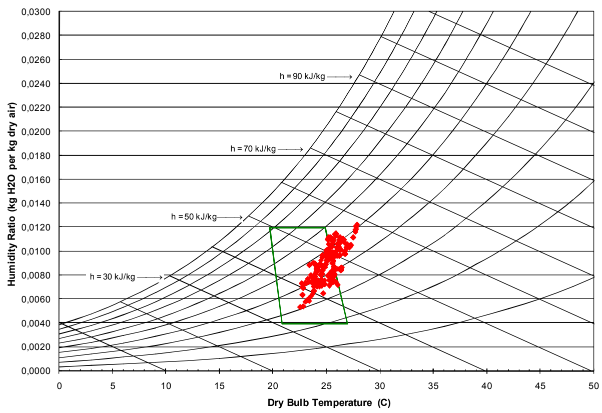

Figure A 18. PH_1_SR_MAY

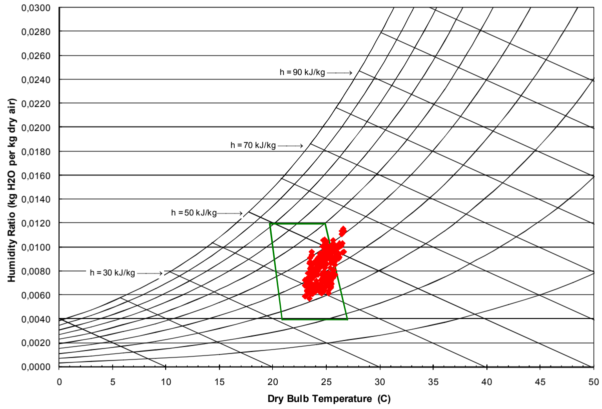

Figure A 19. PH_1_LR_MAY

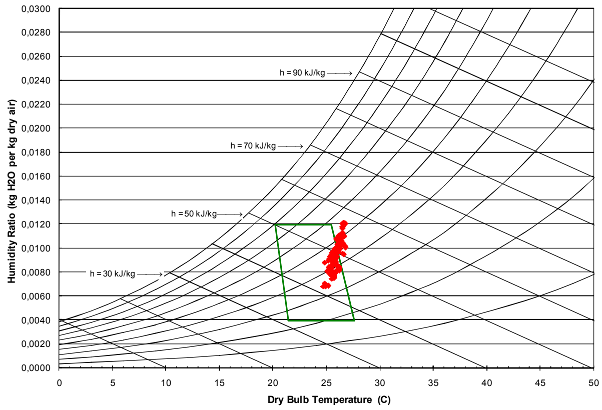

Figure A 20. PH_1_SR_JUN

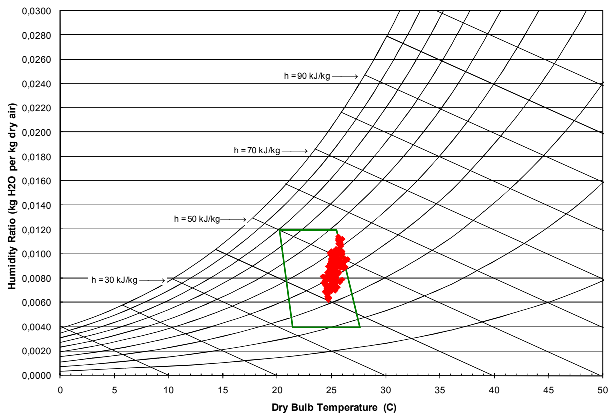

Figure A 21. PH_1_LR_JUN

6.1.3. Passive house apartment 2

PSYCHROMETRIC CHARTS

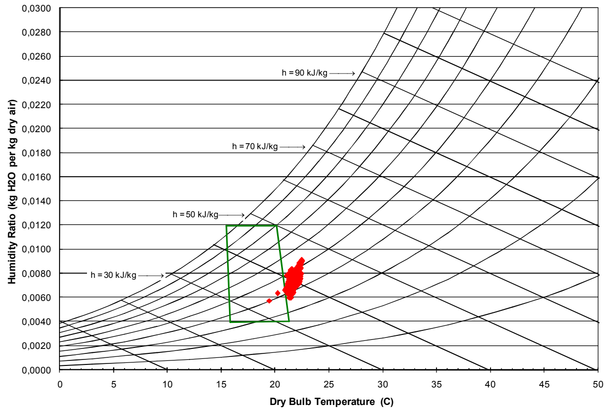

Figure A 22. PH_2_SR_FEB

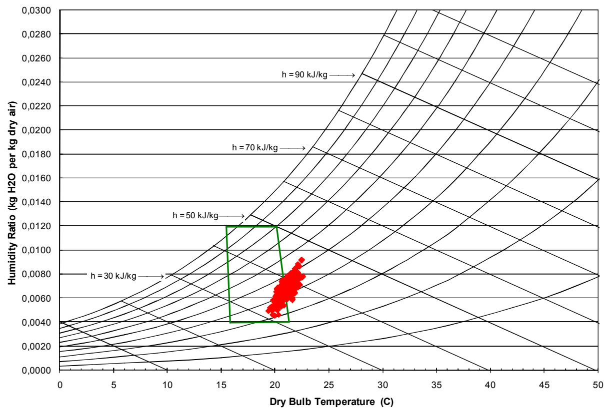

Figure A 23. PH_2_LR_FEB

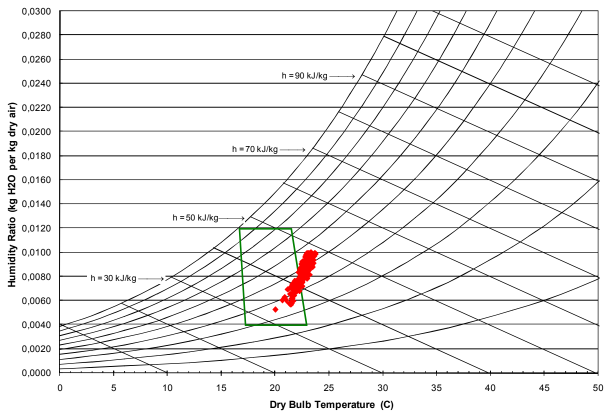

Figure A 24. PH_2_SR_MAR

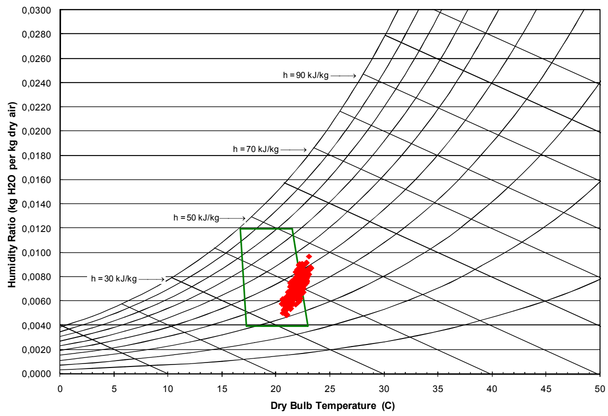

Figure A 25. PH_2_LR_MAR

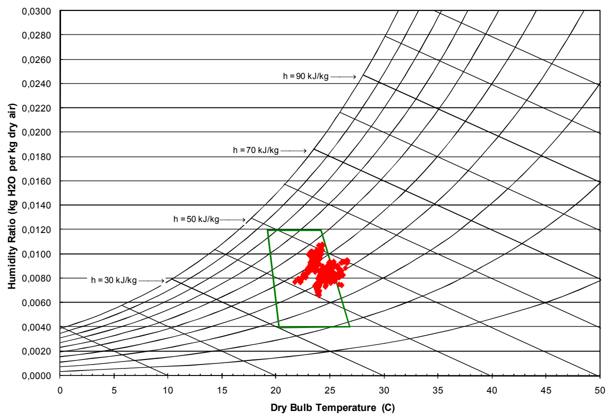

Figure A 26. PH_2_SR_APR

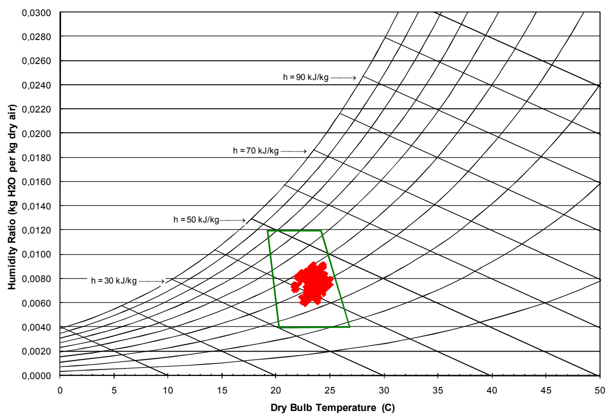

Figure A 27. PH_2_LR_APR

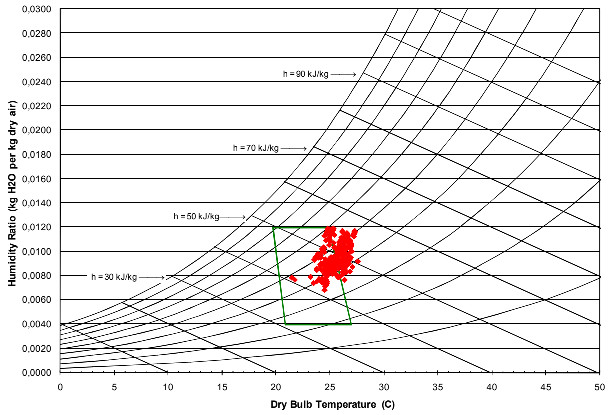

Figure A 28. PH_2_SR_MAY

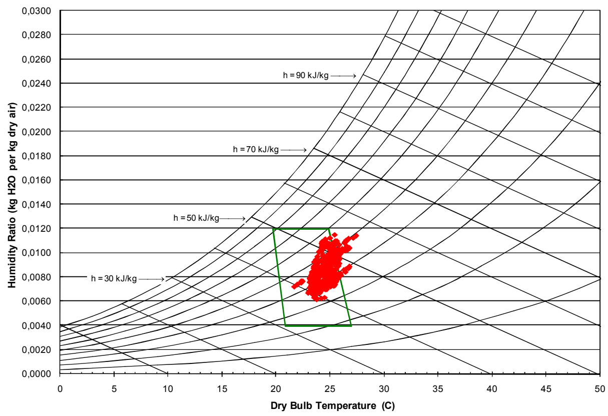

Figure A 29. PH_2_LR_MAY

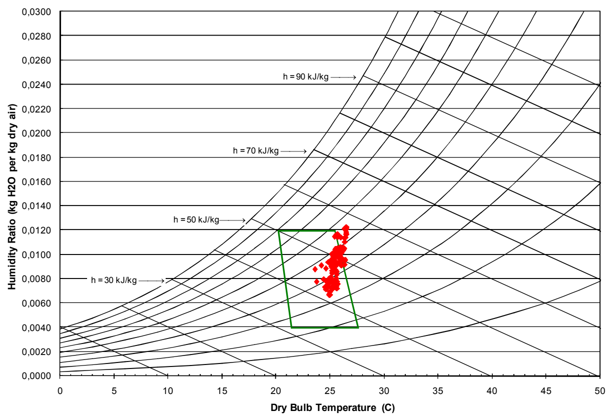

Figure A 30. PH_2_SR_JUN

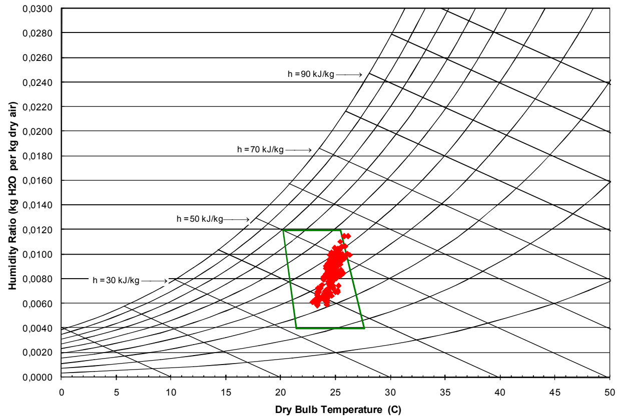

Figure A 31. PH_2_LR_JUN

PREDICTED MEAN VALUE

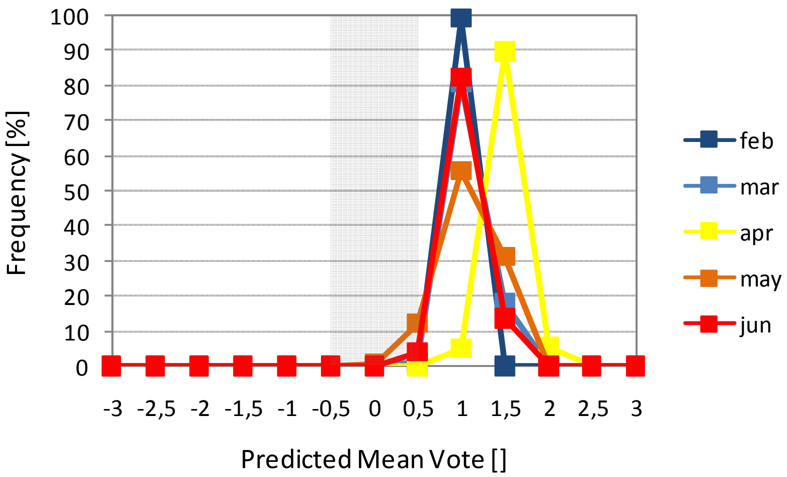

Figure A 32. PH_2_SR_all months

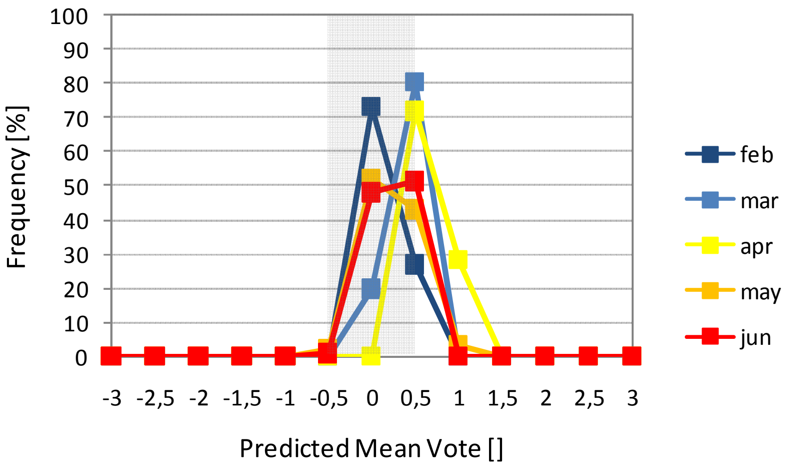

Figure A 33. PH_2_LR_all months

6.1.4. Low-energy house apartment 1

PSYCHROMETRIC CHARTS

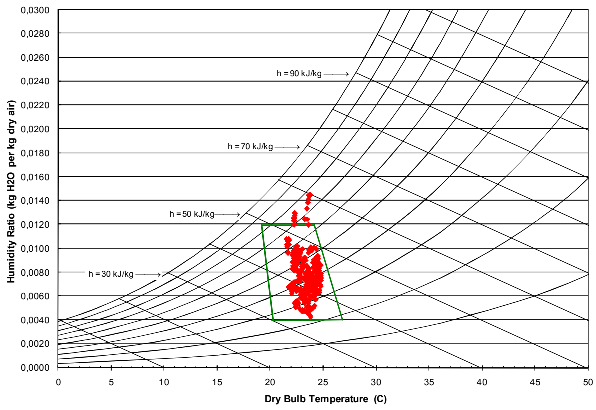

Figure A 34. LH_1_SR_APR

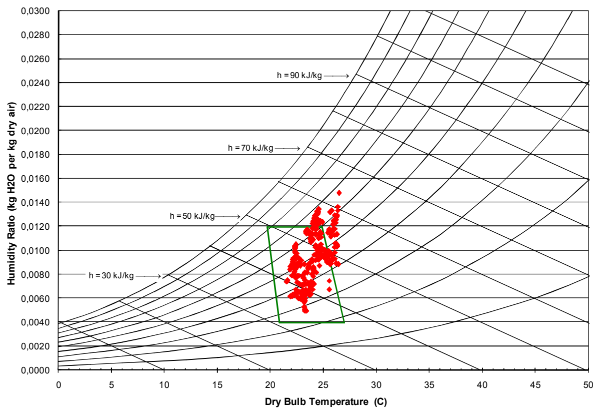

Figure A 35. LH_1_SR_MAY

PREDICTED MEAN VALUE

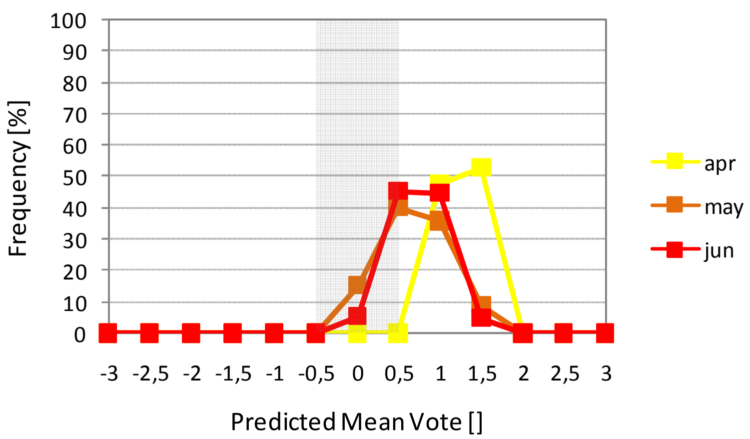

Figure A 36. LH_1_SR_all months

6.1.5. Low-energy house apartment 2

PSYCHROMETRIC CHARTS

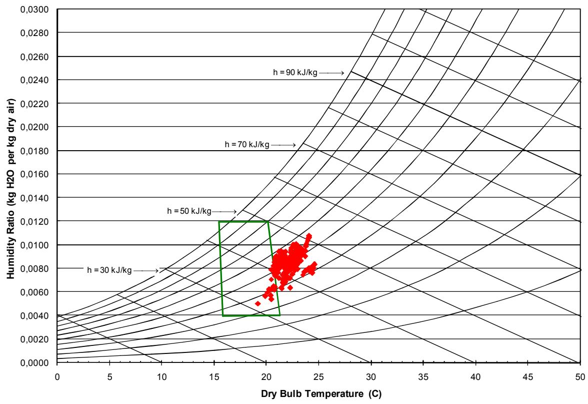

Figure A 37. LH_2_SR_FEB

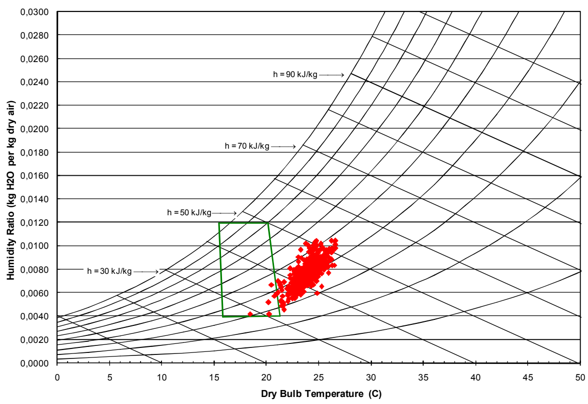

Figure A 38. LH_2_LR_FEB

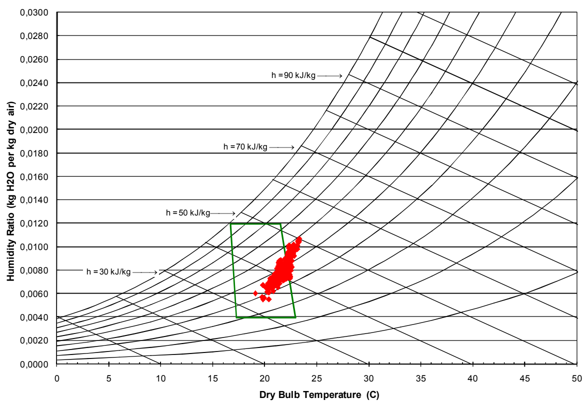

Figure A 39. LH_2_SR_MAR

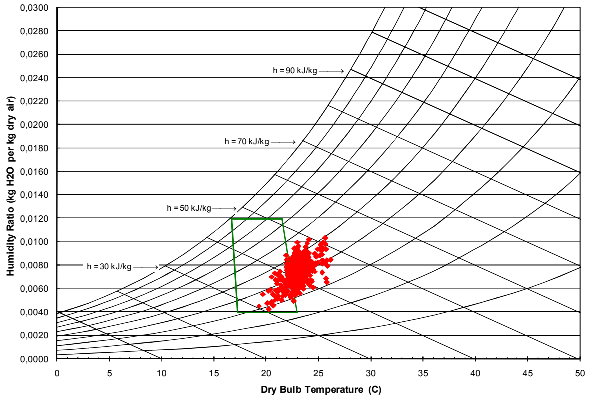

Figure A 40. LH_2_LR_MAR

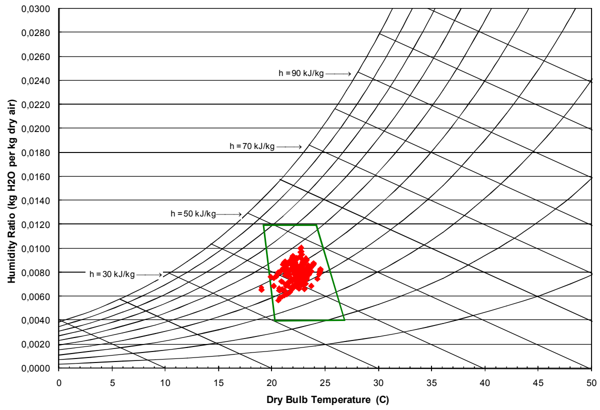

Figure A 41. LH_2_SR_APR

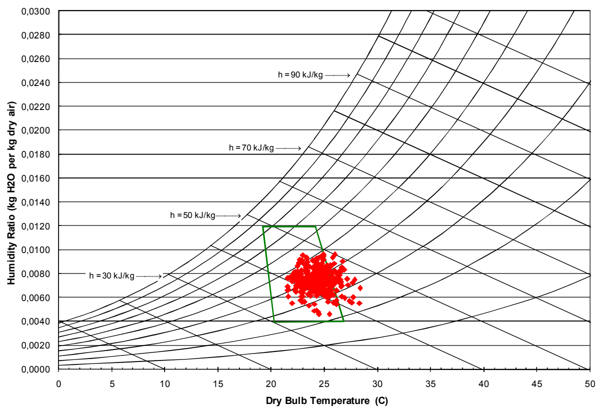

Figure A 42. LH_2_LR_APR

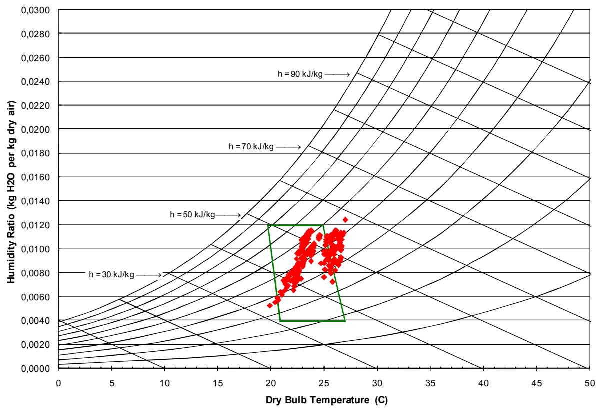

Figure A 43. LH_2_SR_MAY

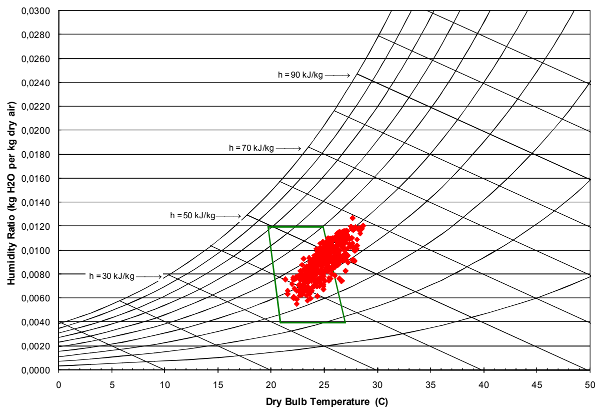

Figure A 44. LH_2_LR_MAY

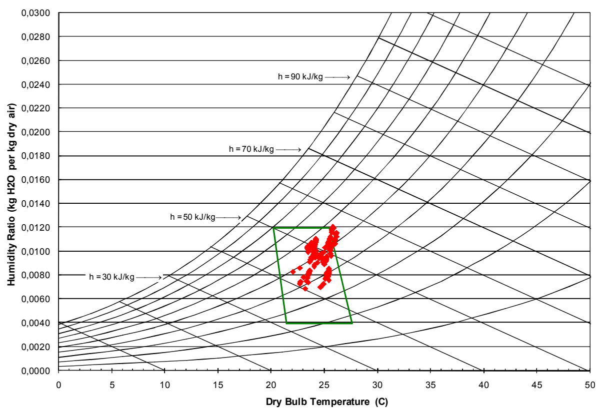

Figure A 45. LH_2_SR_JUN

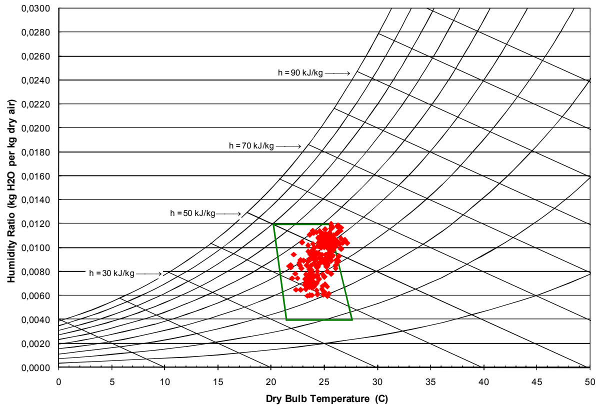

Figure A 46. LH_2_LR_JUN

PREDICTED MEAN VALUE

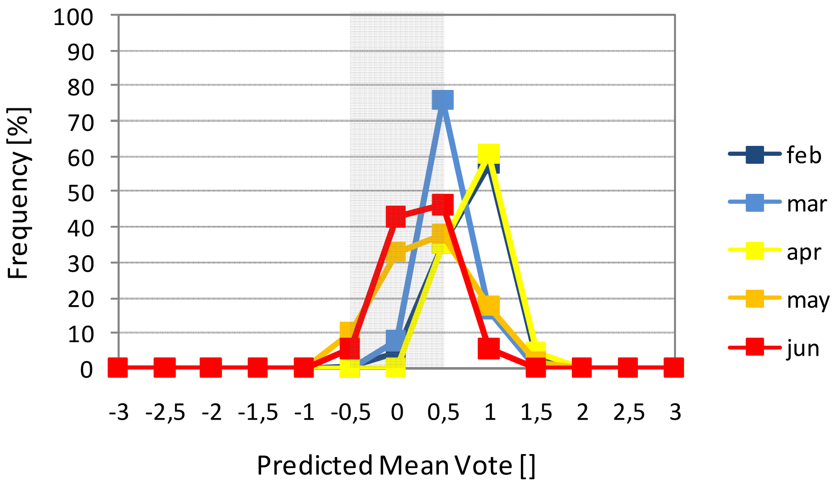

Figure A 47. LH_2_LR_all months

6.2. Questionnaire

The following questionnaire shows the questions that have been posed to the inhabitants of the buildings in form of an interview. It shows the long version that was used for the inhabitants of the monitored apartments; in the short version a few questions were skipped.

FRAGEBOGEN **HAUS:**…………….. **TOP**:……………

1. *ALLGEMEINE FRAGEN*

1.1 Geschlecht

○ männlich ○ weiblich

1.2 Alter

○ Unter 25 ○ 25 – 35 ○ 36 – 45 ○ 46 – 55 ○ über 55

1.3 Berufsbezeichnung:

………………………………………..........

1.4 Wie lange wohnen Sie schon in dieser Wohnung? ……..Jahre …….. Monate

1.5 Wie viele Personen wohnen im Haushalt?

…..………

1.6 Wie viele davon rauchen in der Wohnung(wenn ja wo?)

…………….

1.7 Wie viele Stunden sind Sie pro Tag im Durchschnitt in der Wohnung?

………...…h

1.8 Wie viele Stunden pro Tag am Wochenende?

………….. h

1.9 Wie viele Stunden verbringen sind Sie am Stueck im Schlafzimmer?

…………...h

1.10 Ist ein Sonnenschutz vorhanden?

○ ja ○ nein

1.11 Ist ausreichend Tageslicht vorhanden?

○ sehr viel ○ viel ○ mittel ○ wenig ○ sehr wenig

1.12 Finden Sie die Lueftung zu laut?

○ kaum hoerbar ○ leicht hoerbar ○ deutlich hoerbar ○ laut

1.13 Werden Sie in Ihrer Wohnung durch Laerm gestoert?

○ selten ○ manchmal ○ oft

1.14 Wenn ja, durch welche Quellen?

○ Verkehr

○ Nachbarn

○ Anderes…………

2.1 Wie zufrieden sind Sie mit der Heizung?:

○ sehr zufrieden ○ zufrieden ○ geht so ○ weniger ○ gar nicht

2.2 Wie zufrieden sind Sie mit der Lueftungsanlage?

○ sehr zufrieden ○ zufrieden ○ geht so ○ weniger ○ gar nicht

2.3 Wie zufrieden sind Sie mit der Steuerung der Lueftungsanlage?

○ sehr zufrieden ○ zufrieden ○ geht so ○ weniger ○ gar nicht

2. EVALUIERUNG WOHNZIMMER

2.4 Beurteilen Sie die Luftqualität in Ihrem Wohnzimmer im Winter:

○	○	○	○	○
sehr gut	gut	geht so	schlecht	sehr schlecht

Falls Sie „sehr schlecht" oder „schlecht" ankreuzen, geben sie bitte an warum?

2.5 Beurteilen Sie die Luftqualität in Ihrem Wohnzimmer im Sommer:

○	○	○	○	○
sehr gut	gut	geht so	schlecht	sehr schlecht

Falls Sie „sehr schlecht" oder „schlecht" ankreuzen, geben sie bitte an warum?

2.6 Sind Sie mit der Lüftungsmöglichkeiten in Ihrer Wohnzimmer zufrieden?

○	○	○	○	○
sehr zufrieden	zufrieden	geht so	weniger	gar nicht

Falls Sie „sehr schlecht" oder „schlecht" ankreuzen, geben sie bitte an warum?

2.7 Beurteilen Sie die durchschnittliche Temperatur in Ihrem Wohnzimmer im Winter:

○	○	○	○	○
kalt	eher kühl	neutral	eher warm	heiß

2.8 Beurteilen Sie die durchschnittliche Temperatur in Ihrem Wohnzimmer im Sommer:

○	○	○	○	○
kalt	eher kühl	neutral	eher warm	heiß

2.9 Beurteilen Sie die durchschnittliche Luftfeuchtigkeit im Wohnzimmer im Winter?

○	○	○	○	○
sehr hoch	hoch	mittel	niedrig	sehr niedrig

2.10 Beurteilen Sie die durchschnittliche Luftfeuchtigkeit im Wohnzimmer im Sommer?

○	○	○	○	○
sehr hoch	hoch	mittel	niedrig	sehr niedrig

2.11 Wie oft pro Tag machen Sie eine Fensterlueftung pro Tag im Wohnzimmer im Winter?

……...………

2.12 Wie oft pro Tag machen Sie eine Fensterlueftung pro Tag im Wohnzimmer im Sommer?

……...………

3. *EVALUIERUNG SCHLAFZIMMER*

2.13 Beurteilen Sie die Luftqualität in Ihrem Schlafzimmer im Winter:

○ sehr gut ○ gut ○ geht so ○ schlecht ○ sehr schlecht

Falls Sie „sehr schlecht" oder „schlecht" ankreuzen, geben sie bitte an warum?

2.14 Beurteilen Sie die Luftqualität in Ihrem Schlafzimmer im Sommer:

○ sehr gut ○ gut ○ geht so ○ schlecht ○ sehr schlecht

Falls Sie „sehr schlecht" oder „schlecht" ankreuzen, geben sie bitte an warum?

2.15 Sind Sie mit der Lüftungsmöglichkeiten in Ihrer Schlafzimmer zufrieden?

○ sehr zufrieden ○ zufrieden ○ geht so ○ weniger ○ gar nicht

Falls Sie „sehr schlecht" oder „schlecht" ankreuzen, geben sie bitte an warum?

2.16 Beurteilen Sie die durchschnittliche Temperatur in Ihrem Schlafzimmer im Winter:

○ kalt ○ eher kühl ○ neutral ○ eher warm ○ heiß

2.17 Beurteilen Sie die durchschnittliche Temperatur in Ihrem Schlafzimmer im Sommer:

○ kalt ○ eher kühl ○ neutral ○ eher warm ○ heiß

2.18 Beurteilen Sie die durchschnittliche Luftfeuchtigkeit im Schlafzimmer im Winter?

○ sehr hoch ○ hoch ○ mittel ○ niedrig ○ sehr niedrig

2.19 Beurteilen Sie die durchschnittliche Luftfeuchtigkeit im Schlafzimmer im Sommer?

○ sehr hoch ○ hoch ○ mittel ○ niedrig ○ sehr niedrig

2.20 Wie oft pro Tag machen Sie eine Fensterlueftung pro Tag im Schlafzimmer im Winter?

………………

2.21 Wie oft pro Tag machen Sie eine Fensterlueftung pro Tag im Schlafzimmer im Sommer? ………………

4. EVALUIERUNG INFORMATION

4.1 Fühlen Sie sich ausreichend über die Funktionsweise folgender Gebäudesysteme in Ihrer Wohnung informiert?

	sehr gut	*es geht*	*unzureichend*
Heizung	○	○	○
Lüftung	○	○	○

4.2 Hat in Ihrem Haus eine Schulung über die Funktionsweise der Gebäudesysteme stattgefunden?

○ ja ○ nein

Wenn „ja“, wie bewerten Sie ihre Einschulung in die oben erwähnten Systeme?

○ sehr gut ○ es geht ○ unzureichend

Wenn „nein“, würden Sie sich dafür interessieren?

○ ja ○ weiß nicht ○ nein

4.3 An wen wenden Sie sich im Falle von Problemen mit der Haustechnik (Klima, Licht,…)?

4.4 Sind Sie mit der Betreuung der Haustechnik in Ihrem Haus zufrieden?

○ ja ○ es geht ○ nein

4.5 Meinen Sie dass Sie durch Ihren Umgang mit den Gebäudesystemen den Energieverbrauch beeinflussen können?

○ ja ○ weiß nicht ○ nein

4.6 Bedenken Sie bei Ihrem Umgang mit den Gebäudesystemen die Konsequenzen für den Energieverbrauch?

○ ja ○ weiß nicht ○ nein

5. ABSCHLIESSENDE FRAGEN

5.1 Fühlen Sie sich in Ihrer Wohnung wohl?

○	○	○	○	○
sehr gut	gut	geht so	weniger	gar nicht

5.2 Welche Veränderung, Verbesserung würden Sie in ihrer Wohnung als wichtigste und dringlichste vorschlagen?

5.3 Haben Sie irgendwelche Beschwerden?

	häufig	manchmal	selten	nie
Kopfweh				
Allg. Müdigkeit				
Probleme mit den Atemwegen				
Irritationen der Nase				
Sonstiges:………………………				