The Comfort Houses

Measurements And Analysis Of The Indoor Environment And Energy Consumption In 8 Passive Houses 2008-2011

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Preface

This report describes the results of the Comfort Houses measuring programme conducted by Aalborg University in the period 2008 to 2011. The results from the houses included in the project are examined in detail in 8 house-specific reports. All house-specific reports referred to in this report can be downloaded from www.vbn.aau.dk.

Furthermore, some of the analyses in this report take as their starting point the analyses conducted in the report 'Vurdering af indeklimaet i hidtidigt lavenergibyggeri – med henblik på forbedringer i fremtidens lavenergibyggeri', published by Aalborg University in January 2011 (see list of references).

Aalborg University, January 2012

Tine Steen Larsen
Associate Professor

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1. Outline

This report describes the results of the Comfort Houses measuring programme conducted by Aalborg University in the period 2008 to 2011. The results from the houses included in the project are examined in detail in 8 house-specific reports. The following summary is based on general project conclusions.

Thermal indoor environment

Assessment of the Comfort Houses' thermal indoor environment takes both too high and too low temperatures into account. All measurements are compared to DS/EN 15251 standards, low energy class 2015 and building class 2020 standards and PHI recommendations of house temperatures of +25°C a maximum of 10% of the time.

Overheating

The assessment shows that there is a significant difference between how the houses work thermally. Common to almost all the houses is the fact that they fail to meet the criteria of maximum 100 hours above 26°C and 25 hours above 27°C, respectively, which must be met in future low energy class 2015 and building class 2020 construction. Only two houses manage to meet this requirement.

One of the central conclusions of the assessment of the overheating problem is that it is important in the future to introduce the opportunity for active use of natural ventilation combined with external solar shading in our homes. Active use of natural ventilation means that natural ventilation must be an option, also during the day, when the house is empty, and at the night, thereby making use of the 'free' cooling effect that is available by simply opening the windows. In order to make this possible, and not risk housebreakings, the openings must be incorporated from the beginning of the design phase and the house design must take natural ventilation into account, as it can be difficult to enable natural ventilation once the house is built.

In addition to natural ventilation and solar shading, it has been discussed whether heavy structures (and thus thermal mass) may affect the indoor temperature in a positive or negative direction during a hot summer. It was concluded that thermal mass has a positive effect only as long as it is possible to cool the structure during the night hours, i.e. that the use of thermal mass works only when it is possible to produce a significant air change during the night via natural ventilation. If this is not obtained, the thermal mass may instead increase the overheating problems.

Insufficient heating

A critical aspect in the assessment of insufficient heating problems is how close the maximum effect of the heating system is to the house's design heat loss. If these are relatively close, the building will be considerably more susceptible to discrepancies between the performance of the finished house and the basis of calculation. However, a significant over-sizing of the system will add to the costs of the project; therefore, these parameters must be balanced.

Another aspect of the assessment of problems with insufficient heating is the reduced or missing option of individual room temperature regulation, when air is the only means of heating. This may result in, among other things, cold corner rooms which require increased heating – also highlighted by Minergie® Agentur Bau in their examination of air heating [Minergie® Agentur Bau, 2007]. If the house' distribution of heat between rooms is substandard (e.g. due to sound insulation in the walls between the rooms in question), individual heating regulation in each room may help improve the comfort of these rooms.

Furthermore, the problem with irregular heat distribution between rooms underlines the need for analysing a house as a number of temperature zones, the heat loss and heat loads differing from one zone to the next.

Atmospheric indoor environment

Everything indicates that future houses will be gradually larger and, at the same time, that fewer people will be living in them. That is, a larger number of m² is available per person, which entails that the need for fresh air per m² is reduced – at least when the parameters temperature, CO_2 and humidity are taken into account.

Previously, the amount of ventilation per m² had to meet a set minimum requirement [BR08, BR10], but as the need decreased on account of the above, it should be considered to which degree this requirement should be upheld or whether a reduction and thus a degree of energy conservation should be allowed. On the basis of this line of thinking the Comfort Houses were granted exemption from BR08 and were thus allowed to install demand-controlled ventilation in the houses.

Assessments of the atmospheric comfort show that the airflow in all Comfort Houses is lower than the flow recommended in BR08/BR10. Some do so successfully and still manage to achieve a good indoor environment, but in the houses with lowest air flow assessments of the atmospheric indoor environment are negative.

Assessments of the CO_2 level and relative humidity in the houses show that the CO_2 level is the most critical. CO_2 levels vary from house to house, depending on the amount of ventilation; assessments show that in the living rooms category II is violated 0% to 19% of the time. However, most living rooms show minor violations. In the nurseries and bedrooms violations are more considerable, as there is a greater load per m² in these rooms for a longer period of time. Assessments show that some of these rooms violate the standards almost half the time.

None of the fitted systems monitor the CO_2 level in the houses; however, if demand control with air change rates below 0.5 h^{-1} is allowed in the future, it should be discussed whether this additional investment is necessary. Experience from the Comfort Houses reveals that it is necessary to ensure a good air change in small rooms with a high internal load. As mentioned above, this includes bedrooms and nurseries where the load during the night is considerable. In some cases, nurseries are especially critical, as these rooms are also used during the day.

Daylight

Daylight factors should be included in the future design of low energy houses. The argument for doing so is that it may be possible via increased focus on daylight in homes to reduce the energy consumption for electrical lighting and thus the cost hereof. This project's estimated standard for good daylight is a daylight factor of 2% at the back wall of a given room – in order to thus include the depth of the room in the assessment.

The Comfort Houses' daylight conditions are good in the majority of the rooms. On the basis of the measurements, several examples are given of how the position of the windows in a house can improve the daylight conditions. However, it should be made clear that the risk of overheating should be considered for all south facing rooms. This point is illustrated by an analysis in which actual excessive temperature measurements are compared to the DF and window/floor space. The results hereof are then compared to the BR10 recommendations which recommend a window/floor space factor of 0.15 in building class 2020. Based on experience from the Comfort Houses, a factor of 0.2 would be more correct.

Finally, the importance of the orientation of the windows with regard to energy demand and robustness is analysed. Not surprisingly, the house that has an equal distribution of windows in all directions was the most robust and thus the best suited for any building site, regardless of its orientation. At the same time, a more homogeneous position of the windows in all directions could help prevent problems with dark rooms in the northern part of the house as well as the risk of overheating, glare and stark contrasts in south facing rooms.

Acoustics and noise

In a number of Comfort Houses initiatives have been taken to ensure good acoustics. Measurements of reverberation times in unfurnished rooms have shown considerable differences between houses with acoustics control and houses without. With one exception, though: acoustical ceilings fail to reduce the reverberation time in double heigh rooms with numerous heavy constructions.

Noise from installations is measured at the ventilation system's standard performance. Following the measurements, none of the houses had difficulties meeting category B (<25 dB) standards; however, interviews with the residents in some of the houses indicated that noise from the systems was a nuisance when the systems operated with higher air flows. It is therefore stressed that soundproofing of rooms containing ventilation systems must be given high priority.

Energy

All Comfort Houses are passive houses; this means that they should meet passive house standards. Therefore, the report examines whether this is also the case. This examination is made by comparing calculated and measured energy consumption.

Seeing as the PHPP calculation is based on a series of assumptions (e.g. a room temperature of 20 °C, a standard outdoor climate and a given internal heat load), it is not possible to make a direct comparison of the recorded values and the calculated values. As both the outdoor climate and room temperatures are significant parameters when estimating the energy consumption, these is updated in the PHPP calculation from the measured data. This resulted in approximately a doubling of the calculated expected energy consumption in the house, which clearly illustrates the significance of these two parameters. Most houses have operated with a temperature of 23°C, which in this case has cost approximately 6-8 kWh/m² a year.

Assessment of the *passive house room heat requirement* showed that all but one house meet the passive house requirements. In practice the consumption in two of the houses will be higher than the one measured, though, as both houses have used additional heat sources due to insufficient heating; these were not connected to the measurers used in the measuring programme. Their contribution, however, is expected to be limited. The one house that deviated from the requirement had technical difficulties in the period in question, which may to a certain extent explain the deviation.

Assessment of the *passive house primary energy requirement* revealed great variation in the measured electricity consumption and a factor of 3 between the highest and lowest consumption. Most houses meet the passive house primary energy demand. Two houses do violate the requirement, though, to a considerable extent. Both houses have experienced technical difficulties which may be part of the reason for the deviation.

Assessment of the *passive house excessive temperature requirement* showed that 5 out of 8 houses experience excessive temperature problems in more than 10% of the time. In that connection it is emphasised that excessive temperature calculations are based on an average temperature for the entire house that does not correspond to the indoor environment in a real home. In real homes there is a variation between rooms which is not included in the assessment of the building as a whole. Therefore, excessive temperature assessments should be made at room level.

Finally, the SEL values for the ventilation systems are considered. There is a factor 6 difference between the highest and lowest SEL values, which raises the question of whether requirements for documentation hereof should be met upon delivery of the system.

Users' impact on the indoor environment and energy consumption

The Comfort Houses provide several examples of user behaviour that has proven inappropriate with regard to the indoor environment or energy consumption of a house. Several of these examples place demands on the users to change behaviour that they have brought with them from their former residence. Not all are conscious of or willing to make this behavioural change, and it should be discussed whether a change of behaviour is necessary in order to live in a low energy house. Residents whose behaviour is not 'energy friendly' should also be able to live in low energy houses without feeling that this restricts their behaviour. Therefore, it should never reduce residents' personal comfort – if this is necessary, the low energy concept will never be a success. An obvious idea in future low energy construction is to produce a residents' guide. Not necessarily to change residents' behaviour, but to ensure that they understand the consequences of their behaviour which may in some cases increase the energy consumption in the house quite considerably.

2. Introduction

This report and the related analysis were produced in connection with the project 'Demonstration af energiforbrug og indeklima i 10 danske passivhuse', conducted at Aalborg University in the years 2008 to 2012 in the Comfort Houses. The report will examine the results based on measurements of the indoor environment and energy consumption and, in addition, it will propose useful solutions for future low energy construction.

2.1 Background

Alongside the political developments in energy efficiency in new construction, recent years have revealed increased focus on the construction of low energy houses. This has resulted in several test houses and development projects such as e.g. the Comfort Houses, Green Lighthouse (University of Copenhagen), Fremtidens Parcelhus (Køge, Denmark) and Home for Life (Lystrup, Denmark).

As previously mentioned, this report documents the indoor environment and energy consumption in the Comfort Houses. The Comfort House project was launched in 2007 as a development project at Saint Gobain Isover A/S who wished to communicate knowledge of low energy housing and the principles behind. At the beginning of the project the passive house concept was chosen as the starting point, as this concept was well-known and had been tested for many years in Germany, Austria and Switzerland. The project was intended as a development project, and the passive house concepts were previously unknown to a large part of the participants in the consortia that made a bid for the project. The idea behind making the project a development project was similarly that the project results could be publicly announced and experience from the project help shape future low energy houses – a vision that came true, when the Danish building class 2020 was drafted and e.g. the indoor environment was subject to considerably more focus than previously in the Danish building regulations [Larsen, 2011].

This report will focus in particular on the results from the Comfort Houses, but reference will also be made to other Danish construction and development projects. Furthermore, the analyses are supplemented with experience from Swedish low energy houses, found via literature reviews.

2.2 Analyses of the indoor environment and energy consumption

The report takes as its starting point measurements from the Comfort Houses – i.e. of the indoor environment and energy consumption - starting with the indoor environment. At this point the report considers the various physical parameters that affect the residents in the Comfort Houses. Thus, assessments include both the thermal, atmospheric, lighting and acoustics environments. The parameters are outlined in Figure 2.1. The figure also includes psychological parameters, as different individuals may consider the physical parameters differently depending on their mental condition, and, vice versa, as a person's mental condition can be affected by his or her physical surroundings.

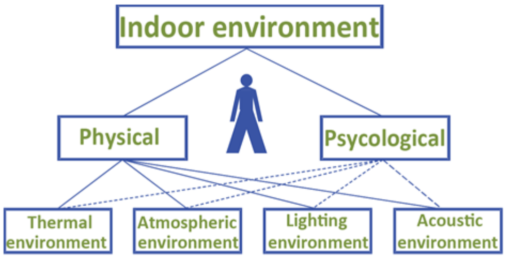


Figure 2.1. Parameters included in the assessment of the indoor environment [Hyldgård et al., 2001].

The assessment of the indoor environment is divided into four chapters, each focusing on one of the four parameters in Figure 2.1. Subsequently, the houses' energy consumption is considered, as are a number of key figures concerning the houses' energy consumption. Afterwards, the users' influence on both the houses' energy consumption and indoor environment is examined. The last chapter summarises all the results and provides suggestions as to how future low energy houses should be designed.

2.3 Use of resident profiles and 'artificial years'

Due to the fact that all the Comfort Houses, contrary to expectation, had not been sold by the time the measuring programme was launched some measurements were made in empty houses. As a number of the project assessments are depended on residents, it has thus been necessary in some of the analyses to create an artificial year based on the months when residents did live in the houses. When 'artificial years' are used, it is mentioned in the analysis.

Resident profiles for the 8 houses can be seen in Figure 2.2. In cases where two families lived in one house, the families are referred to as family 1 and family 2, respectively. Family 1 always represents the family that lived in the house first. The data used in the analyses is, as far as possible, taken from the end of the measuring period, as a significant amount of error corrections and solutions had by then been incorporated into the houses. This data should therefore be the most reliable.

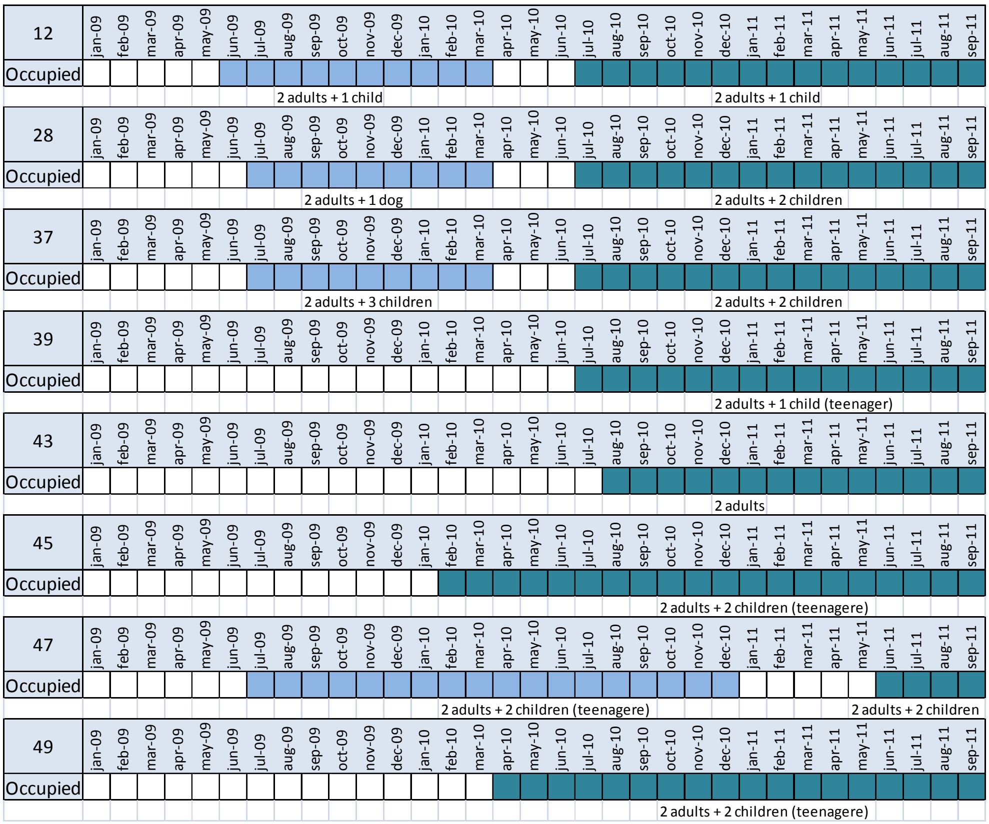


Figure 2.2: Resident profiles for the Comfort Houses in the measuring programme period.

As mentioned, for some houses there are neither residents nor data for a whole year at a time. In these cases the ‘artificial year’ is constructed with all months included, though these do not necessarily stem from the same year.

3. Thermal indoor environment

The assessment of the thermal indoor environment includes both the periods in which it was too warm in some of the houses, but also periods in which it was too cold. The former is described in section 3.3 ‘Risk of overheating’. Subsequently, section 3.4 describes the effect of the thermal mass on the thermal indoor environment. Section 3.5 discusses problems with insufficient heating and section 3.6 looks at the importance of air tighten the house correctly, as a leaky building affects the energy consumption for heating significantly.

3.1 Assessment criteria

A thorough survey of the assessment criteria for the thermal indoor environment can be found in Appendix A, ‘Indoor environment and energy consumption requirements’. Table 3.1 outlines the overall criteria on the basis of which the houses are assessed. The criteria are based on DS/EN 15251.

Thermal indoor environment		Maximum deviation	
	Criterion	Month	Year
General assessment	Category II	12 and 25%	3 and 5%
Excessive temperature	25°C	10%	10%
	26°C	100 h	100 h
	27°C	25 h	25 h
Cooling temperature	20°C	100 h	100 h
	19°C	25 h	25 h

Table 3.1: Assessment criteria for the thermal indoor environment.

The thermal indoor environment is assessed in the different seasons of the year (spring, summer, autumn and winter). All assessments can be found in the house-specific reports, and for each assessment a diagram has been produced, providing a quick overview of the results in the given period. An example of such a diagram is shown in the figure below. The diagram at the top presents the distribution of hours and %, respectively, in categories I, II and III. Category IV indicates the time outside the other categories. When it is stated in the project that category II must be met, the time in category II includes both the number of hours in the part called category II and category I.

The diagram at the bottom indicates whether the room in question is in the low or high end of the scale. E.g. category II- indicates how much of the time the temperature is between 20°C and 21°C – i.e. the

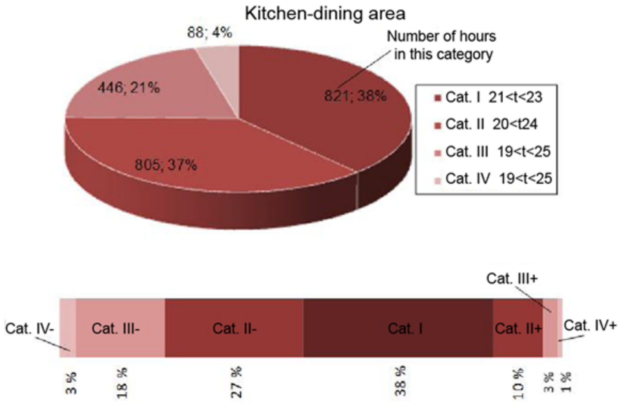


Figure 3.1: List of signs in diagrams.

difference between the lowermost level in category I and the lowermost level in category II. Similarly, category II+ indicates the time in which the temperature is between 23°C and 24°C. For the sake of clarity, a few signs have been omitted from the following graphs.

3.2 General assessment of criteria

The Comfort Houses' thermal indoor environment was assessed on the basis of the criteria presented in Table 3.1. Living room assessments are included in the table, as this room is considered the main room of the house.

		<19 [h]	<20 [h]	>25 [%]	>26 [h]	>27 [h]	Deviation from Cat. II [%]
HOUSE 12 Kitchen-dining area	2009 **	36	521	42	2220	904	31
	2010 **	66	480	21	861	392	15
	2011	0	0	27	703	93	8
HOUSE 28 Living room	2009 **	0	158	27	1313	560	17
	2010 **	32	317	23	953	427	14
	2011	0	0	32	1770	381	37
House 37 Living room	2009 **	114	599	25	1819	1568	28
	2010 **	374	671	40	2355	1533	35
	2011	0	49	21	801	295	10
House 39 Living room	2009 *	0	0	40	2360	1550	27
	2010 **	1360	1989	24	779	266	32
	2011	0	0	6	100	28	1
House 43 Living room	2009 *	0	54	52	4157	3505	48
	2010 **	1128	1495	22	1457	1147	34
	2011	91	199	15	600	280	9
House 45 Living room	2009 *	1101	1411	44	3305	2092	54
	2010 **	1187	1862	5	118	11	23
	2011	13	271	7	44	5	4
House 47 Living room	2009 **	4	159	28	1988	1587	25
	2010	719	926	16	732	370	19
	2011 **	1	1	30	1651	1241	19
House 49 Living room	2009 *	805	1297	23	1391	884	31
	2010 **	611	697	11	481	205	13
	2011	0	1	4	62	10	1

* Not occupied, ** partially occupied

Table 3.2: The result of the thermal indoor environment assessment. Red numbers indicate that the assessment criteria were not met. Green and black numbers indicate that the criteria were met.

It makes no sense to evaluate the houses' indoor environment for periods in which they were empty. Therefore, the overall assessment in Table 3.2 above indicates, next to each year, when the house in question was inhabited. Further details are evident from Figure 2.2. Information about the other rooms in the house can be found in the house-specific reports.

It is evident from the assessments of the thermal indoor environment that there is a considerable difference between how the houses work thermally. Common to almost all the houses is that they fail to meet the low energy class 2015 and building class 2020 criteria of 100 hours above 26°C and 25 hours above 27°C, respectively. However, houses 45 and 49 do manage to get below the mentioned thresholds. Assessment of the PHI recommendation of a house temperature of +25°C a maximum of 10% of the time shows that houses 39, 45 and 49 meet the criteria. The same houses observe the maximum deviation from category II on an annual basis which, depending on the chosen level, must be below 3% or 5%. It should be mentioned, though, that the requirements apply to the use of a standard weather data set, which is not the case with these measurements. This is discussed in more detail in chapter 7.

3.3 Risk of overheating

A critical part of the design phase is the design and position of solar shading as well as ventilation of hot air away from the house to avoid overheating. As low energy houses have a low air permeability and are well-insulated, a considerable degree of solar radiation through the windows will soon heat the house. Therefore, it is important to consider solar shading and natural ventilation at the beginning of the design phase to avoid subsequent problems with overheating which can be difficult to correct once the house is built.

3.3.1 General experience

Previous experience from low energy houses has shown that some houses get very warm very quickly, resulting in discomfort. High temperatures arise in part as a result of a large number of south facing window sections which are often poorly protected from solar radiation and, in part, as a result of limited ventilation options. It should be noted, though, that there is limited experience with the scope of this problem in older houses built according to previous building regulations, but older houses do also experience this problem during hot summer months.

The use of natural ventilation and solar shading would be able to reduce and in many cases avoid excessive temperatures. Previously, solar shading was not considered a necessity in new houses, but in the future it should be included as early as the beginning of the project.

Another experience from present-day low energy construction is that the design phase places great emphasis on documenting the building's energy consumption, whereas the house's indoor environment is neither assessed nor documented to anywhere near the same extent. Documentation of the house's energy consumption must be provided to the authorities via Be06. The programme punishes excessive temperatures, and many use the size of this 'punishment' to evaluate the extent to which the indoor environment is satisfactory. However, it should be pointed out that an energy calculation programme cannot be used to ensure a satisfactory indoor environment. Documentation of the indoor environment should be based on a calculation of the indoor environment, i.e. documentation of e.g. the thermal indoor environment during the summer period (assessment of excessive temperatures), the level of CO_2 in the air, daylight conditions and so on. Low energy class 2015 and building class 2020 will make such documentation of the thermal indoor environment mandatory.

Considering the experience from corresponding projects in Sweden, whose climate is similar to the Danish climate, the experiences are the same. The extensive analysis conducted by Ulla Janson in her 2010 doctoral thesis gathers experience from 4 Swedish projects with a total of 93 houses on a passive house level [Janson, 2010]. On the subject of overheating, one of the overall conclusions of her report is that it is true for many of the residents who experience overheating problems that their energy consumption for electrical appliances is considerable. That is, their internal load is significant and thus contributes to high indoor temperatures.

A 171 m² single-family house built in 2007 in Lidköping near the Swedish lake Vänern has massive overheating problems. Here the lack of opportunities for opening the windows and solar shading result in very unhappy residents in the summer period. Upon completion of the measurements, a window that could be opened was added, reducing the excessive temperatures considerably [Janson, 2010].

The same problem with excessive temperatures can be found in a 2005 energy renovation project including 40 flats in Alingsås near Göteborg, but in this case only the third floor residents complain of excessive temperatures, which are also confirmed by the measurements. Of the two flats in which the indoor environment measurements are made, one flat has no solar shading and the other has indoor window blinds. The ground floor flats in the building in question have no problems with excessive temperatures. The reason for this has not been analysed further [Janson, 2010].

In two other projects including 40 and 12 flats, respectively, the homes are fitted with massive overhangs that protect against the sun [Janson, 2010]. Both projects experienced minor complaints of excessive temperatures, which illustrates the importance of solar shading in future low energy houses.

3.3.2 Experience from the Comfort Houses

A number of houses have significant problems with overheating during summer, while others have efficient solar shading which ensures that the house does not overheat during summer.

Figure 3.2 and Figure 3.3 show the summer period results from houses 28 and 47, respectively. Both houses meet category II approximately 70% of the time. The rest of the time the indoor temperature is almost always above 26°C.

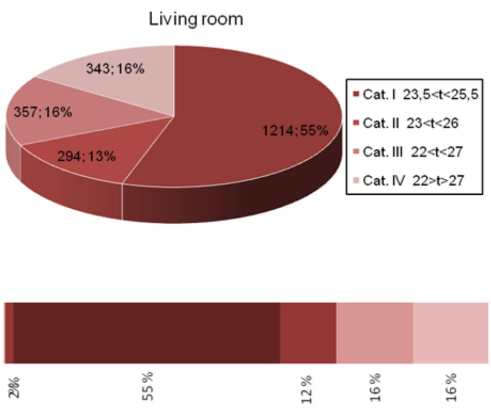


Figure 3.2: House 28: Distribution of hours in comfort classes for the summer situation in living room in 2010.

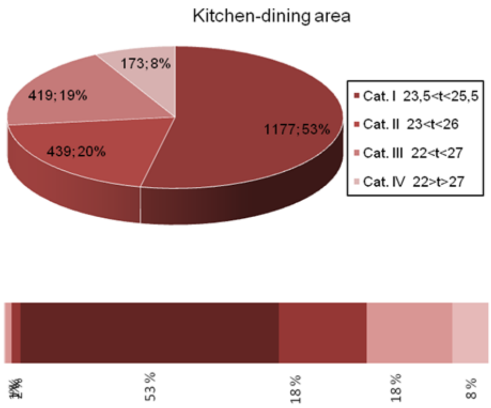


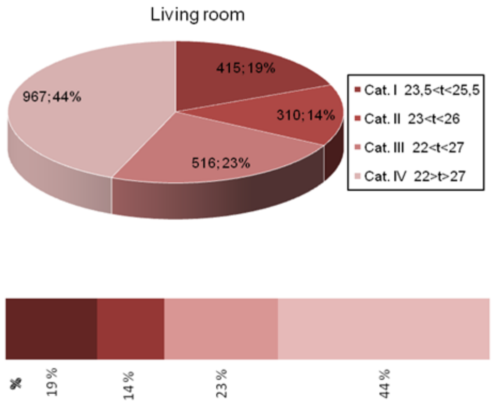
Figure 3.3: House 47: Distribution of hours in comfort classes for the summer situation in living room in 2010. Figure 3.4: House 47: Distribution of hours in comfort classes for the summer situation in kitchen-dining area in 2011.

Common to these two houses is that the windows in the rooms in question are only partially or not at all protected from the sun. The houses are presented in Figure 3.4 and Figure 3.5. In house 28 one out of three window sections in the living room are covered by the permanent overhang. Furthermore, indoor curtains have been fitted. House 47 has neither indoor nor outdoor solar shading.

Figure 3.5: House 28: Example of partial solar shading.

Figure 3.6: House 47: No solar shading.

Figure 3.6 and Figure 3.7 demonstrate the effect of indoor solar shading. In the summer 2010 the residents in house 37 had just moved in. This summer levels exceed category II a large part of the time and all violations are at the high end of the scale, i.e. temperatures above 27°C. In 2011 the problem is reduced considerably after fitting indoor window blinds in the house.



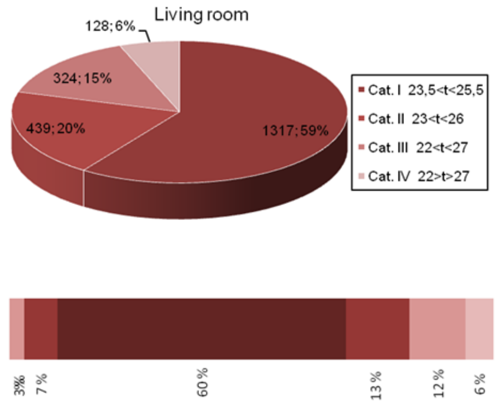


Figure 3.7: House 37: Distribution of hours in comfort classes for the summer situation in living room, 2010.

Figure 3.8: House 37: Distribution of hours in comfort classes for the summer situation in living room, 2011.

Via efficient solar shading three of the houses ensure comfortable summer temperatures for their residents. The different types of solar shading are examined in the next section (section 3.3.3), but the effect of the good solutions are evident in Figures 3.8 to 3.12.

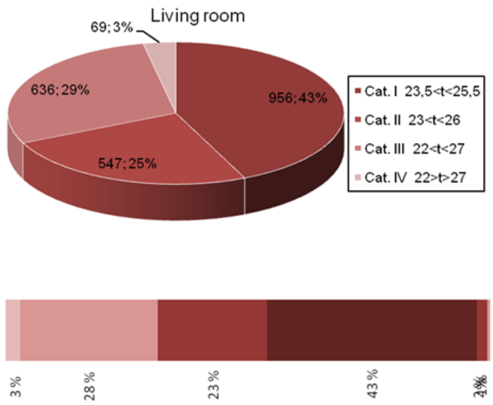


Figure 3.9: House: 39 Distribution of hours in comfort classes for the summer situation in living room in 2010. Figure 3.10: House 39: Distribution of hours in comfort classes for the summer situation in living room in 2011.

Figure 3.11: Solar shading in house 39.

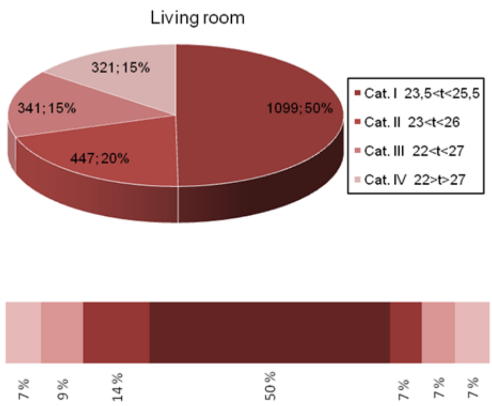


Figure 3.12: House 43: Distribution of hours in comfort classes for the summer situation in living room in 2011.

Figure 3.13: Solar shading in house 43.

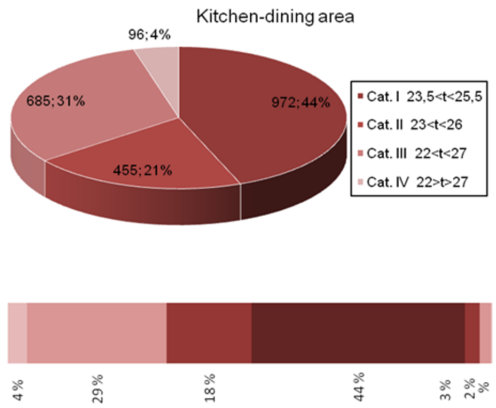


Figure 3.14: House 45: Distribution of hours in comfort classes for the summer situation in kitchen-dining area in 2010.

Figure 3.15: Solar shading in house 45.

Common to the three houses is that they meet category II approximately 70% of the time. Assessing the violations it is evident that they are not caused by excessive temperatures, but in the majority by lower temperatures – i.e. temperatures below 23°C. In houses 39 and 45 this is the case for almost all violations. House 43 also shows violations due to higher temperatures. The results from these houses show efficient use of solar shading in the house design. It should be noted, however, that the room in house 45 that has no form of solar shading clearly demonstrates the effect of the lack of solar shading. This room and the houses with no solar shading experience the same problems – namely excessive temperatures.

In addition to the three above-mentioned houses, house 49 shows few excessive temperature hours. This house has no form of outdoor solar shading, but manages to cool the house in another way. The house has a skylight which may be the cause of the comfortable indoor environment in the house, as a skylight can ensure the necessary air change via natural ventilation.

3.3.3 Integrated solar shading

solar shading did not used to be a standard solution in private homes, but the experience described in the previous section demonstrates that it will be necessary in the future to consider this option in Danish low energy construction.

The different forms of Solar shading vary significantly in terms of type and technology, but common to all forms of solar shading is that the protection should be external, as this provides the most efficient protection [SBi202]. The external solution does not allow the sunlight inside the building, as indoor solutions do, and efficient external solar shading can therefore reduce the solar radiation by as much as 70-80% and at the same time maintain parts of the view.

Figure 3.14 presents four examples of solar shading. Illustration a. shows automatic integrated solar shading in house 43 which can be hidden underneath the facade and is thus only visible when used. Illustration b. shows permanent solar shading fitted above the lowermost window in house 45. Here the structure itself works as a form of solar shading for the uppermost part of the window section. Illustration c. shows manual solar shading in house 39 in the form of shutters, which can be used to cover the windows, along with fixed protection above the windows. In Illustration d. the idea is that in time deciduous plants will grow and come to act as protection above the terraces on the first floor and ground level, respectively.

a. b. c. d.

Figure 3.16. Examples of external solar shading.

There are advantages and disadvantages to all the different forms of solar shading, and the chosen solution will therefore differ from project to project. The advantage of the automatic solution (a.) is that the solar shading will be activated even though the residents are not at home. Thus, they avoid coming home to an overheated house. The disadvantage to this solution is the price and maintenance.

Manual solar shading (c.) with adjustable slats or shutters comprises a reliable solution with a minimum of maintenance, but correct use of this solution requires that the residents remember to cover the windows e.g. before they leave the house in the morning.

In the design of permanent solar shading (b. and c.) the sun's position in the sky is used to calculate the length of the overhang. The calculation method often enables the sunlight to enter the building during winter, but not during summer. It must take into consideration a symmetrical time around 21 June when determining the solar shading, as this is the day the sun is highest in the sky. If the calculation is made only for 21 June, the sun will enter the building all other days. This problem is illustrated in Figure 3.15, demonstrating that the sun in the given example will enter the building in e.g. August where there is still no need for it; but morning and afternoon situations, when the sun is low in the sky, can also be critical.

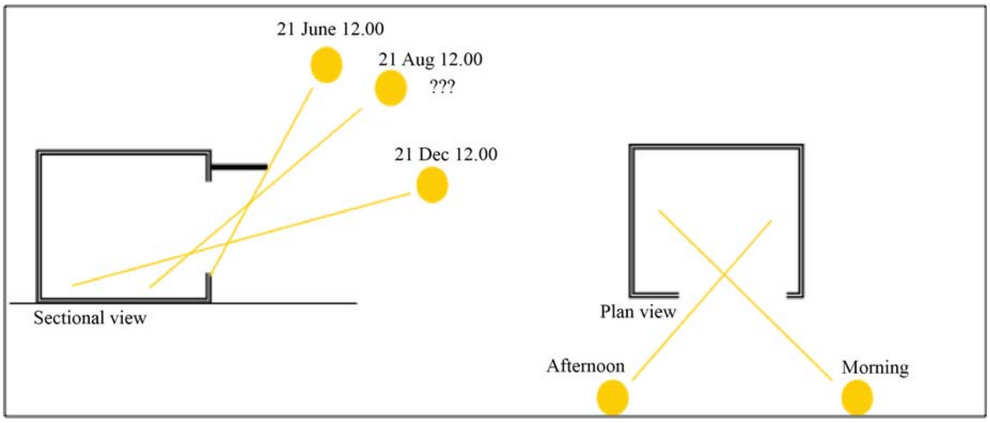


Figure 3.17. Assessment of the building as solar shading.

3.3.4 Active use of natural ventilation

As efficient use of natural ventilation may prevent excessive temperatures during day and night, it is essential that it can be used actively. To ensure this possibility, the use of natural ventilation must be integrated into the house design from the beginning of the design process.

The most efficient ways of ventilating hot air out of the house are either via cross ventilation or stack ventilation (requires that there is more than one level in the house between the openings). Additionally, these can be supplemented with single sided ventilation: one window in the room is opened. The three types of ventilation are illustrated in Figure 3.16. Stack ventilation shown on the right can also be combined with cross ventilation.

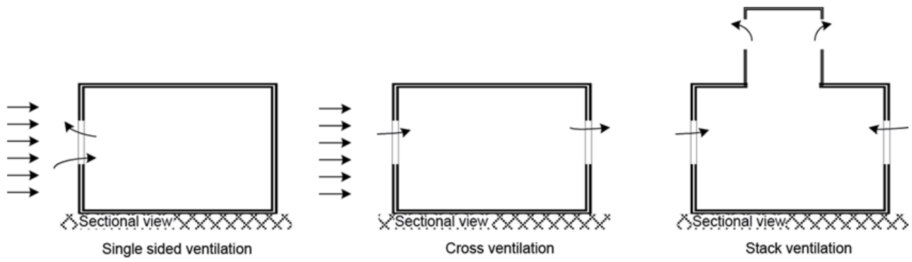


Figure 3.18. Principles for natural ventilation.

To ensure the optimum solution for the use of natural ventilation it is essential that windows, or alternatively ventilation hatches, can be opened at all hours. I.e. that it is possible to keep the windows open during the day, when the residents are not at home, and during the night when everyone is asleep. Naturally, secure openings must be used, in agreement with existing insurance rules.

An example of the integration of natural ventilation from the beginning of the design phase can e.g. be found in Home for Life in Lystrup near Aarhus where ventilation openings for natural ventilation are an integrated part of the design of the building. Here natural ventilation is used as the only form of ventilation in the summer period. In the transition periods, spring and autumn, hybrid ventilation is used. Depending on the external temperature, the system uses either mechanical or natural ventilation and thus ensures the best possible comfort and the lowest possible energy consumption. During winter natural ventilation is used as a supplement to mechanical ventilation with heat recovery. The window openings are controlled automatically, and the principle of this ventilation strategy is shown in Figure 3.17.

In the summer period natural ventilation is based on the room temperature, opening the windows to cool a room; but the CO_2 level and relative humidity (RH) may also affect the opening level. The opening level is calculated on basis of the desired maximum air change rate, weather data etc. The user can control how active a regulation he or she wants.

If there is no need for cooling, but a high CO_2 level is measured, the control can switch to pulse ventilation, ventilating the house using short ventilation periods. Alternatively, the user can set the system to pulse ventilation at fixed times.

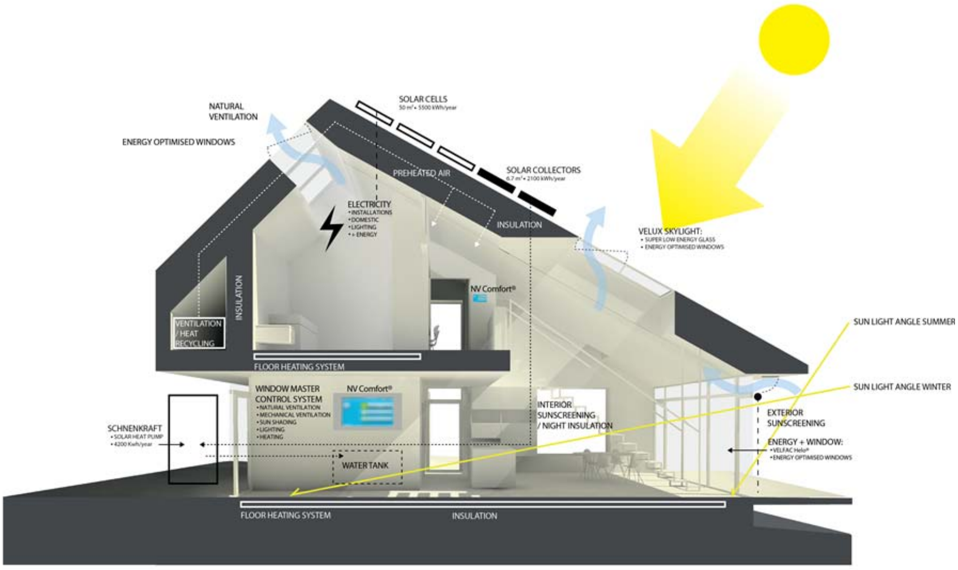


Figure 3.19. The principles for natural ventilation in Bolig for Livet [VKR, 2010].

To reduce the energy consumption as much as possible, the ventilation system only starts up when needed, if one or more zones require hybrid assistance. Every zone with the hybrid option can call for hybrid assistance based on temperature, CO_2 or relative humidity measurements.

As mentioned, a number of the window openings in this example were intended for natural ventilation already at the beginning of the project. Hence, theft protection may also have to be incorporated, seeing as the system must be able to work in an empty house as well as during the night, as night cooling is a part of the ventilation strategy. The position and design of the openings can be seen in Figure 3.18.

Figure 3.20. Position of ventilation openings in Home for Life [VKR, 2010].

3.4 Effect of thermal mass

In the Comfort Houses a number of different construction solutions were used – from (heavy) concrete constructions to (light) wood constructions. In that connection it was discussed whether thermal mass is important in a low energy building to be able to store surplus heat and thus level out and avoid very high indoor temperatures.

Experience has shown that the thermal mass can cause problems if it is not cooled down during the night – i.e. if natural ventilation fails to produce the necessary cooling effect for cooling down the construction. Empirical results show that an air change rate of approximately 4-8h^{-1} during the night is required to ensure a sufficient cooling effect in constructions with a high thermal mass [Artmann et al., 2008]. If the construction is not cooled down, the rooms will be uncomfortably warm; in this case a lighter construction would have been more suitable, as such a construction can be cooled down much quicker via natural ventilation.

Just as the thermal mass in some cases can level out excessive temperatures during summer by storing the heat in the construction, it may also contribute to a reduced heating bill in the heating season. Figure 3.19 shows how the heating requirement changes when the thermal mass of the building is reduced. The analysis was conducted in connection with the Comfort House project and based on PHPP calculations from three different houses in the project [The Comfort Houses: erfaringer, 2010].

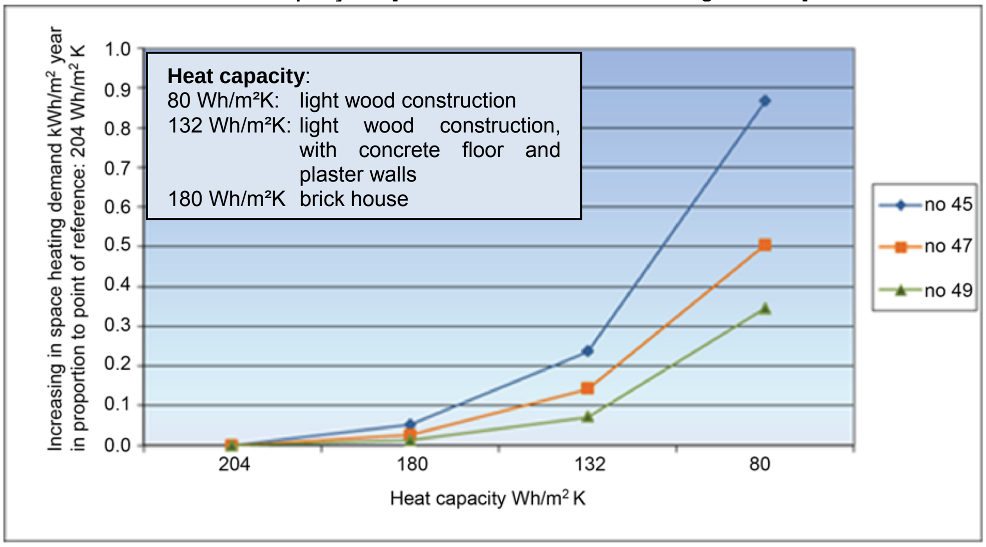


Figure 3.21. Changes in the heating requirement when the house's heat capacity changes [The Comfort Houses: erfaringer, 2010].

It is evident from the calculation that the heating requirement increases when the construction's thermal mass is reduced, as its ability to store heat in periods with e.g. high solar radiation is reduced. The extra heating requirement can vary from 0.3 and 0.9 kWh/m² per year between heavy and light constructions. The largest gap is between light and very light constructions (132 to 80 Wh/m²K); here the inclination of the curve changes considerably.

The increase of the graph depends on the overall structure of the house, as evident in the example with three different houses. At the same time, the increase in the heating requirement is minimal, and if this turns out to be more inconvenient in the summer period than useful during winter, it should once again be considered to which extent a large thermal mass is beneficial in low energy housing.

3.5 Insufficient heating

As the houses' heating requirements are reduced, the correct dimensioning of technical installations and calculations of the design heat loss become still more critical, as the houses often come close to the threshold between the amount of heat that can be provided and the amount of heath that is lost. This chapter will outline experiences with insufficient heating in low energy houses and the critical points in the design process in this context.

3.5.1 General experience

In the design of low energy houses small amounts of energy often have to be supplied to heat the house in the winter period. If a system design is chosen with a possible added effect that borders on the calculated heat loss, as soon as the actual conditions in the house deviate from the basis of calculation it will cause situations in which the house's heating capacity is insufficient. I.e. situations in which the external temperature is lower than -12°C or the desired room temperature is more than 20°C; situations in which the ventilation system defrosts and is unable to provide the required inlet temperature; situations in which the residents are at work or on holiday and the internal load is reduced; or other situations in which the situation in the house does not correspond to the calculations and thus require an increased effect from the house ventilation and/or heating system.

A number of different heating solutions are used in low energy houses today, ranging from houses heated exclusively by ventilation air to houses with a traditional water-based heating system in the form of radiators and floor heating. Air heating is the cheapest solution, as it involves no expenses for installing radiators and/or floor heating; however, the air heating solution can also result in poor thermal comfort in the house, as it complicates or eliminates the opportunity of regulating the rooms individually. An overall conclusion in an extensive Swedish project with a total of 93 houses was that all the residents who were dissatisfied with the heating preferred radiators to air heating [Janson, 2010]. The reason for this was not given, but it may be due to the fact that the residents wanted to be able to influence the temperature in their homes.

A water-based heating system would enable the residents to regulate the temperature in all the rooms of the house individually. This system could either be in the form of floor heating or radiators. The advantage of radiators is that they react quickly upon regulation. Among others, the residents in Home for Life realised this and would have chosen radiators rather than floor heating in all rooms if they had subsequently been given the opportunity to choose differently [VKR, 2010].

It is important, though, in connection with all types of heating systems that a design heat loss is calculated for all rooms individually – as in previous standard constructions with a significant heat loss. This is to ensure that rooms placed in the corners of the house (and therefore contain two outer walls) can be heated on the same terms as the rest of the house.

User behaviour is also an important factor in the assessment of the issue of insufficient heating – e.g. significant cooling of the house in the winter period by manual ventilation via the windows. The house should be fitted with mechanical ventilation which must be able to handle the demand for fresh air during cold periods, as mechanical ventilation uses heat recovery and the heat loss as a result of ventilation is reduced significantly.

Assessment of experience from similar Swedish studies also shows a tendency to problems with low temperatures in the winter period. Thus, 50% of the residents in a 2006 project including 40 flats in Värnamo in southern Sweden wanted higher temperatures in the winter period – the remaining 50% were satisfied [Janson, 2010].

In another project from 2005, involving energy renovation of 40 flats in Alingsås near Göteborg, low temperatures (as low as 16.9°C), among other things, caused problems due to one resident's electricity-conserving behaviour. The electricity consumption in this flat is included as internal load to the heat balance, but this resident who lived alone is very observant of his electricity consumption. This entails that the flat in question uses almost no electricity. The internal heat load that normally comes from electrical equipments is therefore minimal, which means that the heat load from this source is missing. The towel dryer that was meant to complement the heating system is also electrically powered and the resident, therefore, does not turn it on. The solution in this case was that the housing association chose to pay for the power given to the towel dryer [Janson, 2010].

A 2001 project by Isakson analyses the energy consumption and indoor environment in 20 terraced houses built as low energy houses. The residents have difficulties heating the houses; it is especially difficult in the gable house to maintain a comfortable room temperature level. All the houses' ventilation systems have a 900 W heating coil. This is not sufficient in the gable house; therefore, electrical radiators are installed subsequently. A number of the residents light candles and are very conscious of when they e.g. should use the tumble drier to keep the house warm [Isakson, 2006].

3.5.2 Experience from the Comfort Houses

There have, in a number of The Comfort Houses been problems with insufficient heating. The problems were solved temporarily by installing electrical radiators and gas heaters, but seeing as these heat sources are significantly more expensive to use than e.g. the geothermal heat pump that a lot of the houses are fitted with, in the autumn 2011 other solutions were sought. The autumn 2011 solutions do not affect the measuring programme, but in connection with the installation of electrical radiators and other additional heat sources the energy consumption for these sources was not recorded. The implication of this is that it is not possible to provide an exact picture of the energy consumption for space heating in all houses, as the energy consumption from the additional heat sources are not measured.

Additional heat sources were installed subsequently in the following houses:

- House 28: 2 electrical radiators are installed in the nurseries in the west end of the house in the autumn 2010. In the autumn 2011 they tried to solve the problem via increased air flow to the room. At first, the furniture in the room almost blocked it. In addition, an floor heating area in the living room is connected to the heat pump.
- House 37: Electrical radiator installed in January 2010. In May 2010 the electrical radiatior was replaced with a radiator connected to the geothermal heat pump, as the electricity solution was far too expensive. Neither the energy for the electrical radiator nor for the water-based radiator is measured.
- House 45: Gas heaters are installed in November 2010. These have subsequently been replaced with 3 electrical radiators.

3.5.3 Case study: Heat loss from critical room

The following case study is included to show how problems with insufficient heating can occur and how they can be solved. In this case the problem arose as a result of a combination of different undesirable parameters; however, as mentioned in section 3.5.1 a single deviation from the design conditions can create problems in cases where the maximum possible added effect is close to the design heat loss.

The house used in this case study is house 37, presented in Figure 3.20. The same figure shows the position of equipment measuring the temperature in the house's living room and the north-western room (green markers). All the instruments are placed in h = 1.6 m. Further information on these measurements can be found in the house-specific report for house 37.

Figure 3.22. The position of the equipment measuring the temperature in living room and room (green markers) as well as the ventilation inlet (blue circles) and exhaust (red circles).

The house is equipped with a Nilan VP18 compact system and should be heated exclusively via air heating. Nevertheless, floor heating via a water-based system has been fitted in the bathrooms (heat from a geothermal heat pump), but this contribution was not included in the house's heat supply, when the dimensioning of the effect from the ventilation air was done.

Considering the temperatures measured in the living room and the north-western room, respectively, the progress can be seen on Figure 3.21 for December and Figure 3.23 for January. In December the indoor temperature evidently begins to drop in the middle of the month when the external temperature drops. However, throughout the month it is difficult to maintain a comfortable temperature in the north-western room.

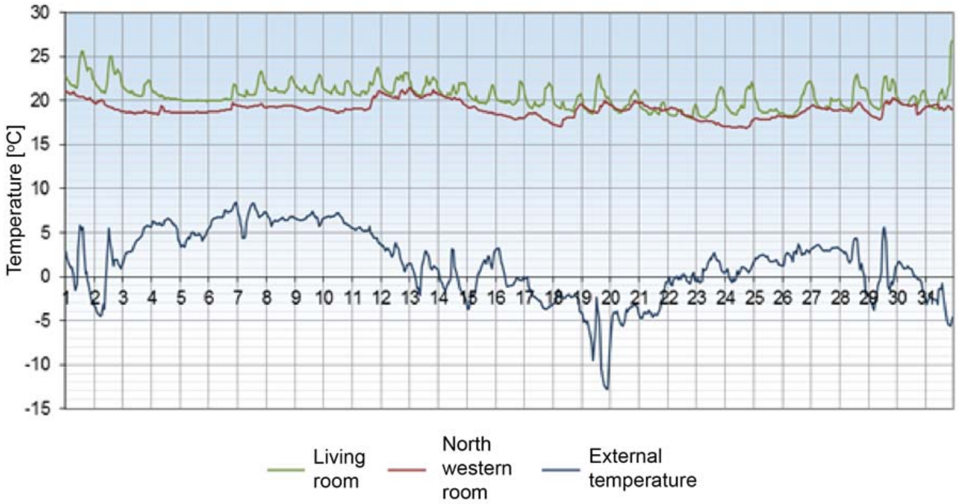


Figure 3.23. Temperatures measured in December 2009.

The temperature drop as a result of a corresponding external temperature drop shows that the system has reached it maximum capacity and is thus unable to heat the house. Evaluating the thermal comfort in December reveals the distribution presented in Figure 3.22. It is evident from the figure that the house has been far from thermally comfortable (i.e. temperatures above 20°C for category II); especially the north-western room is critical.

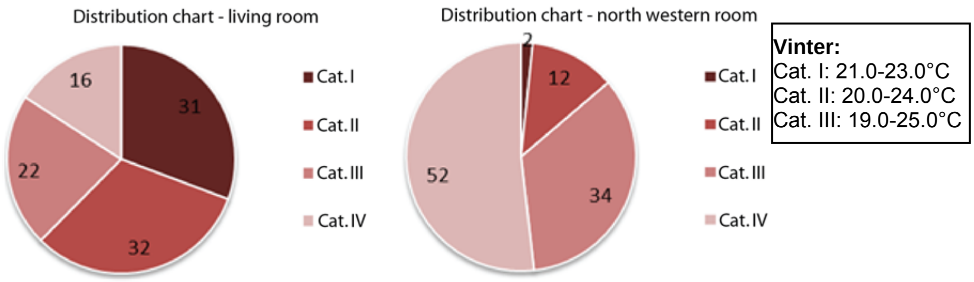


Figure 3.24. Assessment of the thermal indoor environment in the living room and north-western room, respectively, December 2009.

The heating problems continue until 9 January 2010 (cf. Figure 3.23) when an electrical radiator is installed subsequently. After installing the radiator it is possible to reach reasonable levels of comfort in the living room; however, the temperature in the room in question remains too low and relies on additional heating, not via the radiator due to poor heat transfer between the rooms in the house.

As was the case with overheating, the distribution of temperatures in the house is not homogeneous, which again stresses the importance of regarding the house a number of distinct temperature zones in the calculation; the heat loss and heat loads differ from one zone to the next.

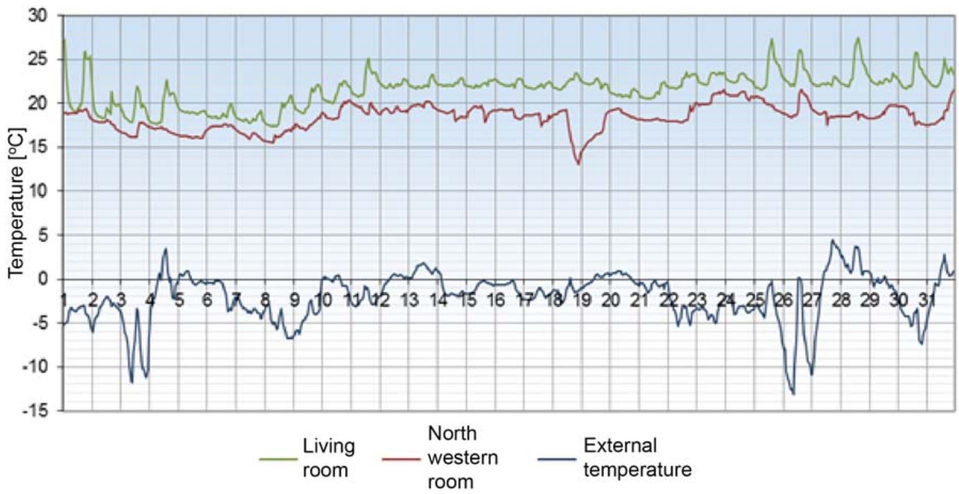


Figure 3.25. Temperatures measured in January 2010.

What is the problem?

There are a number of sources of error in the case study above, and as mentioned in section 3.5.1 it often takes a single parameter that deviates from the calculations to cause problems. In this case the problem was subsequently solved by installing a radiator in the living room, connected to the geothermal heat pump, the capacity of which is sufficient. Had its capacity been insufficient, a possible solution could have been a permanent electrical radiator, which would not have been desirable with regard to the energy cost.

In this case the inlet temperature from the house's ventilation system comprises one source of error; according to the calculations it should be 52°C. This is the temperature recommended by the German passive house institute and the one that is normally used in German passive houses [Feist, 2007]. However, this high temperature depends on a high inlet air speed to ensure a high degree of ventilation effectiveness, as hot air rises and therefore naturally wants to lie as a cloud under the ceiling. This is a general problem, and it should be pointed out that fittings which facilitate a significant impulse in the inlet air should be used in cases with an increased inlet temperature.

Assessments of the inlet temperature, as the one in this example, demonstrate that the temperature is never above 49°C and that the average temperature is only 35.4 °C, cf. Figure 3.24. In the period following 17 December, when the external temperature begins to drop, the inlet temperature is even lower. At the same time, many defrosting periods result in a further reduction of the inlet temperature.

The disadvantage of using air heating is also evident in an analysis conducted in connection with the choice of heating systems for the Minergie® and Minergie®-P houses in Switzerland. The conclusion here is that the disadvantages of using this type of heating system exceed the cost reduction of not using water-based heating [Minergie® Agentur Bau, 2007]. The EBST has chosen to follow this recommendation in the future building class 2020; here it is no longer possible to use only air heating.

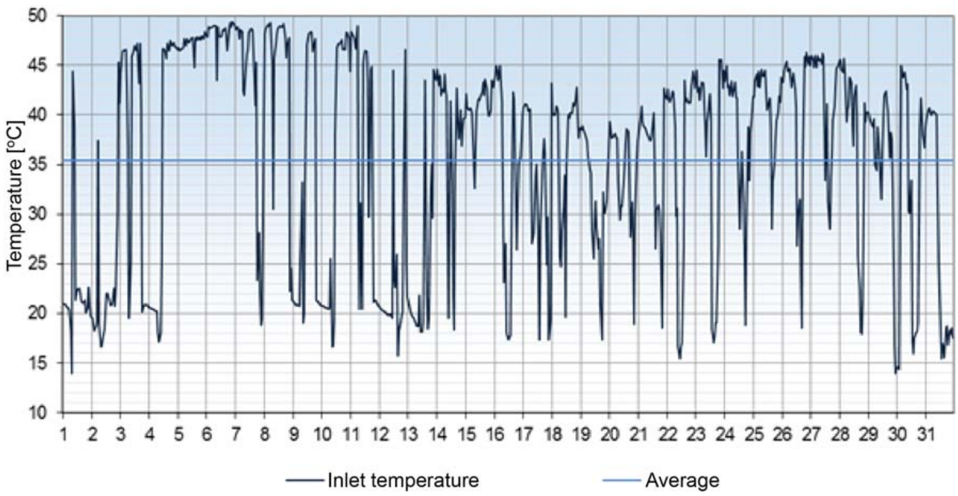


Figure 3.26. The inlet temperature from the compact system, December 2009.

Another source of error in connection with the heating problem can be lack of control of the heat loss in the north-western room. If this heat loss exceeds the heat supply via the ventilation air, it will not be possible for the temperature in the room to reach a comfortable level, as there are no additional heating sources, e.g. radiators or floor heating.

A third element that may affect the energy requirement and thus lead to cold rooms due to insufficient heating options is the user's habit of using the windows to vent the house for longer periods during winter. In this period the ventilation system should manage all ventilation, recycling the heat in the exhaust air using the system's heat exchanger. This does not happen when the house is aired via the windows, and the heat loss caused by this kind of airing is thus especially demanding on the ventilation system. More or less the same problem occurs in houses with no form of wind screen, as large air flows will disappear when the exterior door is opened. A wind screen would be able to reduce this heat loss significantly.

3.6 The effect of airtightness on the heating requirements

An important parameter with regard to the extent of the heating requirements in a house is its airtightness. If the construction is leaky, infiltration means that cold air enters the house which thus depends on heating from regular heat sources. If these are desi
gned with a small or no margin of safety, an increased infiltration rate, compared to the basis of calculation, may quickly result in heating problems.

To illustrate this problem, the energy requirement of a 181 m² two-storey house corresponding to BR08 low energy class 1 is determined. The only parameter that varies in these calculations is the infiltration rate during winter (i.e. the heating season in which this problem can occur). The result is shown in Figure 3.25. It is evident from these calculations of the energy requirement how important the house's airtightness is, as the result of a leaky building with a high infiltration rate will be evident on the heating bill. The figure below includes an infiltration rate that corresponds to that of a standard building and a low energy class building, respectively, as defined in BR10.

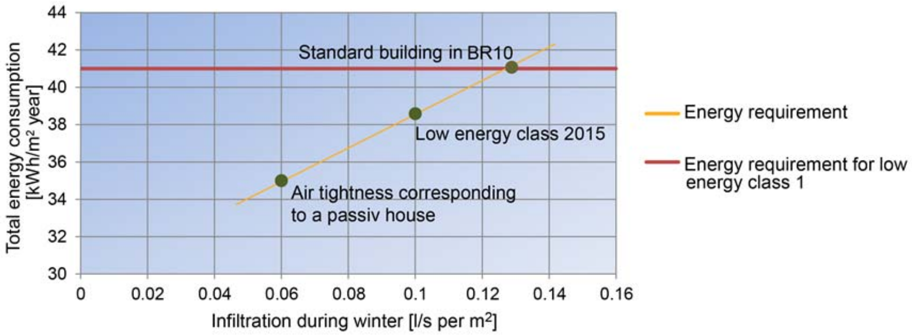


Figure 3.27. The energy requirements as a result of the infiltration rate [Larsen et al., 2011].

In addition to the requirements for airtightness in Danish regulations, the infiltration rate corresponding to the airtightness requirement in a passive house is included in order to illustrate the advantage of this degree of airtightness, which in this case results in an additional cost reduction of almost 4 kWh/m² a year, compared to the Danish 2015 low energy class building.

3.7 Summary

The indoor environment in the Comfort Houses has been evaluated on the basis of both too high and too low temperatures. All measurements are compared to DS/EN 15251 requirements, to requirements for the 2015 low energy class buildings and building class 2020 as well as recommendations from PHI of a indoor temperature of +25°C a maximum of 10% of the time. It is evident from the assessment that the houses differ significantly with regard to how they work thermally. Common to nearly all the houses is the fact that they fail to meet the 2015 low energy class and building class 2020 criteria of a indoor temperature of +26°C for a maximum of 100 hours and a indoor temperature of +27°C for a maximum of 25 hours, respectively. Only two houses meet this requirement. On the basis of the PHI recommendation of a indoor temperature of +25°C for a maximum of 10% of the time and a maximum deviation from category II 3 or 5% of the time 3 houses pass the test.

Overheating

One of the significant conclusions of the assessment of the overheating problem is that it is important in the future to incorporate active use of natural ventilation and external solar shading into our homes. Active use of natural ventilation means that it is also possible to vent the house naturally at night or during the day when the house is empty and thus make use of the ‘free’ cooling effect available by simply opening the windows. In order to make this possible, without risking housebreakings, the openings in the house must be included from the beginning of the design phase and the design of the house must take the opportunity of natural ventilation into account, as it can be difficult to create this opportunity once the house is built.

Apart from the inclusion of natural ventilation and solar shading, it has been discussed to which extent heavy constructions (and thus thermal mass) can affect the indoor temperature in a positive or negative direction during a hot summer. It was concluded that the effect of the thermal mass is positive only as long as it is possible to cool the construction during the night, i.e. that the use of thermal mass works when it is possible to create a sufficient air change during the night via natural ventilation. If this is not achieved, the thermal mass will instead increase the overheating problems.

Insufficient heating

One the most critical points in the assessment of insufficient heating problems is how close the maximum effect of the house's heating system is to the design heat loss. If these two values are relatively close to each other it will make the building more sensitive to discrepancies between the house in operation mode and the bases of calculation. However, a significant oversizing of the system will raise the cost of the project, so these parameters must be balanced.

Another aspect of the assessment of the problem with insufficient heating is the reduced or missing opportunity to regulate room temperatures individually when air is the only source of heating. This may, among other things, result in cold corner rooms in a house that requires additional heating, as emphasised in Minergie® Agentur Bau's study of air heat for heating private residences [Minergie® Agentur Bau, 2007]. If the heat distribution between rooms is poor (e.g. due to sound insulation in the walls between individual rooms), a heat supply that is regulated individually may also help improve the comfort of a given room.

The problem with uneven heat distribution between the rooms further underlines the necessity, in the calculations, of considering the house a number of temperature zones, as heat losses and heat loads differ from one zone to the next.

4. Atmospheric indoor environment

Assessments of the atmospheric indoor environment compare measurements of the CO_2 level, relative humidity and ventilation rates in order to assess, among other things, whether the ventilation rates in the houses were sufficient. This assessment is significant, as the Comfort Houses have been granted exemption from the BR08 to use demand-controlled ventilation. A form of ventilation which in this project has entailed that the air change in all the houses is less extensive than the one prescribed by the building regulations.

4.1 Assessment criteria

A thorough outline of the assessment criteria for the atmospheric indoor environment can be found in Appendix A: 'Indoor environment and energy consumption requirements'. Table 4.1 demonstrates the overall characteristics of the criteria on the basis of which the houses have been evaluated. The criteria are based on DS/EN 15251.

Atmospheric indoor environment		Max. deviation	
	Criterion	Month	Year
CO_2	Category II	12 and 25%	3 and 5%
	Category II	8 h running	-
Relative humidity	Category II	12 and 25%	3 and 5%
	Category II	24 h running	-
	φ<45%	1 month consecutive except 10 hours	-
	φ>75%	1%	-

Table 4.1: Assessment criteria for the atmospheric indoor environment.

4.2 Overall assessment in relation to the assessment criteria

The atmospheric indoor environment in the Comfort Houses was assessed on the basis of the criteria given in Table 4.1. The assessment presented in Table 4.2 includes the living room, as this room is considered the primary room of the house. However, bedrooms and nurseries are often more critical than the living room with regard to the CO_2 level. These rooms are addressed in section 4.4. Furthermore, information on other rooms can be found in the house-specific reports.

As there is no point in evaluating the houses' indoor environment in the periods in which they were unoccupied, for each year the table notes when the house in question was inhabited. Further detail about this matter is given in Figure 2.2.

It is important in connection with the assessment of the CO_2 level in the houses to take into consideration when the houses are inhabited. It is evident that some of the houses observe the recommended maximum deviation from category II on 3%. House 39 and house 12, however, reveal a number of deviations from the recommendations. In house 39 the air change is lower, which can explain the deviations. In house 12 the air change is higher, but in this case the residents use the living room a large part of the time. Furthermore, in the autumn 2009 the house experienced problems with the system that led to a high CO_2 concentration in the house. The number of 8-hour deviations from category II generally corresponds to the number of periods outside category II.

		CO_2-concentration		Relative humidity			
		Deviation from cat. II [%]	8-hours periods with deviation from Cat. II [-]	Deviation from Cat. II [%]	24-hours periods with deviation fromCat. II [-]	whole months with φ<45%	Time with φ>75%
HOUSE 12 Kitchen-dining area	2009**	16	36	9	13	3	0
	2010**	9	11	30	32	3	0
	2011	13	26	12	9	2	0
HOUSE 28 Living room	2009**	0	0	20	12	3	0
	2010**	1	1	52	17	2	0
	2011	1	0	20	20	2	0
HOUSE 37 Living room	2009**	11	12	14	9	2	1
	2010**	6	12	32	27	2	0
	2011	3	1	5	1	2	0
HOUSE 39 Living room	2009*	0	0	24	11	2	0
	2010**	19	46	21	11	2	0
	2011	16	23	4	2	3	0
HOUSE 43 Living room	2009*	0	0	39	17	3	0
	2010**	3	5	43	16	3	1
	2011	3	4	29	19	2	1
HOUSE 45 Living room	2009*	0	0	15	8	2	0
	2010**	7	11	16	14	2	1
	2011	3	3	2	1	3	0
HOUSE 47 Living room	2009**	8	7	29	17	3	0
	2010	10	18	28	16	3	1
	2011**	0	1	33	19	2	1
HOUSE 49 Living room	2009*	0	0	11	6	2	0
	2010**	13	25	29	22	2	1
	2011	6	3	6	4	2	0

* Unoccupied, ** Partially occupied

Table 4.2: The result of the indoor environment assessment for atmospheric indoor environment. The red text indicates that the assessment criteria are not met. Green indicates that the criteria are met. Black indicates that there is no specific criterion.

The assessment of the relative humidity shows that only a few of the houses are able to meet the assessment criterion of a 3% or 5% deviation from category II. The transgressions are caused by low RH figures that occur during winter. Most houses have no problems with too high RH figures. There is a tendency, however, that to high RH figures in bedrooms in direct connection with bathrooms occurs, as damp spreads from the bathroom and is not exhausted as it should be.

All houses achieve RH<45% periods of a minimum of a month, just as there are no problems in the other end of the scale with RH>75%.

4.3 Demand-controlled ventilation

BR10 makes it possible, to a limited extent, to use demand-controlled ventilation in multi-storey buildings. A number of technologies are still in the process of being developed and several new solutions will soon be introduced. Nevertheless, finding a way to control the systems poses a significant challenge. Ventilation control on the basis of the expected parameters – CO_2, relative humidity or temperature – is associated with a series of problems, as a reduced air change which keeps the above-mentioned parameters on an acceptable level may cause problems with other parameters such as radon or formaldehyde.

On the basis of the above, it is therefore important to determine which parameters must be taken into account in connection with demand-controlled ventilation.

4.3.1 General experience

The idea of using demand-controlled ventilation comes from an energy-economic viewpoint. It is debatable whether the ventilation system needs to use energy to ventilate an empty house or to change a significant volume of almost clean air in houses with a low internal load, if it is instead possible to adjust the air flow when the demand decreases or disappears and, similarly, to increase the air flow when the need for fresh air is increased. Before switching to demand-control in homes and a possible reduced air change it is important, however, to analyse – in addition to the typical control parameters like CO_2, relative humidity and temperature – the effect of a reduced air change with regard to radon or formaldehyde, which are not directly measurable today and therefore cannot be taken into account in ventilation system control.

In connection with demand-controlled ventilation, it is often discussed which parameter(s) the system must be regulated according to. Humidity is often used as a parameter; it has, among other things, been examined for flats in Bergsøe et al. [2008]. As too high relative humidity can, among other things, cause problems with condensation on windows, increased amounts of house dust mites and, at worst, humidity and rot in constructions, this parameter is extremely relevant when determining a parameter for the control of the ventilation rate.

Another relevant parameter is the experienced air quality; however, this parameter is not directly measurable and is therefore often related to CO_2 measurements, as both parameters depend on the number of people inhabiting the house.

In houses used for private residences using CO_2 as a control parameter is not normal [Bergsøe et al., 2008] [Maripuu et al., 2009]. One of the arguments against it is the price of CO_2 sensors compared to humidity sensors, as CO_2 sensors are significantly more expensive than humidity sensors. Another argument is that the CO_2 level of a house with a normal internal load will not pose a problem as long as the air change is kept at the recommended 0.35 l/s per m² (net); however, if this figure is lowered, it is also relevant to measure the CO_2 level in the air.

4.3.2 Experience from the Comfort Houses

Considering the RH measurements in the Comfort Houses, the relative humidity – the monthly average – rarely drops below 70%. This only occurs a few summer months with extensive rains. Instead, the winter months are characterised by very dry air, which could be improved by reducing the air change. The air change is already low in a lot of the houses, and it can therefore only be reduced to a limited extent, as it must still be possible to heat the house (in so far as it is heated with ventilation air), and at the same time it is important to ensure that it does not increase the CO_2 levels too much. To ensure this, the CO_2 level should be included as a control parameter in this case.

Table 4.3 shows the measured air flows in the Comfort Houses. The air flows are given as the average for the periods in which the houses were inhabited. It is evident from the table that some of the houses have low air flows and that the air flow levels in some of the houses are lower than the flows recommended in BR08 (= 0.35 l/s per m² [net]).

Average air flow	12	28	37	39	43	45	47	49
Occupied period	0,24	0,13	0,13	0,16	0,14	-	0,24	0,17
May-September	0,25	0,16	0,15	0,16	0,14	-	0,27	0,15
October-April	0,24	0,12	0,12	0,16	0,14	-	0,24	0,16

Table 4.3: Measured air flows in the Comfort Houses in inhabited periods. Given in l/s per m².

House 39 which deviated significantly from category II in the atmospheric comfort assessment has an air change that is less than half of the level recommended in BR08. In the winter period where the natural ventilation supplement is at a minimum, the house only managed to meet the category II level 25% of the time in the nursery, and the transgressions were often as high as 2000 ppm above the outside level. The problem in the nursery is characteristic of and seen in a number of the houses. The same problem is also found in the bedrooms and occurs during the night due to the constant load from people in rooms with a somewhat smaller volume per person than the other rooms in the house. The assessment of the relative humidity also presents a number of problems. Nevertheless, the problematic period in terms of RH is pushed to late summer and autumn, which often have periods with high RH levels. RH assessments show that the above-mentioned rooms only meet category II levels 57% of the time. During winter houses with a very low air change experience minor problems with low RH values (i.e. dry air); however, this is as mentioned at the expense of high CO_2 level figures.

Therefore, it is important to point out that it should be possible in bedrooms and nurseries to maintain a sufficient air change to avoid these problems, either via mechanical or natural ventilation. Using natural ventilation in the winter period is not advisable, though, as it entails no heat recovery and the heat loss is thus increased unnecessarily. The above also illustrates why it is necessary with a CO_2 sensor in the ventilation system when you allow an air change below 0.35 l/s per m² (net) and the internal load is not reduced correspondingly.

The air flow per person evident from the assessment of the internal load is calculated in Table 4.4. It is shown that the air change rate also differs significantly when the internal load is included in the assessment.

Average air flow	12	28	37	39	43	45	47	49
Occupied period, calculated pr. person	13,99	5,70	6,00	8,21	10,36	-	9,35	6,68

Table 4.4: Measured air flows in the Comfort Houses in inhabited periods. Given in l/s per person. Children are included as 0.5 person, teenagers the same as adults.

4.4 The CO_2 concentration

Evaluating and comparing the houses' CO_2 levels it is also important to consider the load in the individual houses. This is done by looking at the resident profiles shown in Figure 2.2. Furthermore, it is important to take the amount of ventilation into account, as it also affects the CO_2 level.

The following presents results from house 39, which reveals the most significant deviations from category II, though not the lowest air change, and from houses 12 and 47, which have the highest air change. Two adults and one teenager live in house 39; families with one and two children, respectively, live in houses 12 and 47. All the houses are analysed during a winter period, as this is the period with the lowest degree of natural ventilation and thus also the period with the highest CO_2 levels.

The CO_2 level also rises during winter in house 39. Category II is met 53% of the time in the living room, meanwhile category II only is met 25% of the time in the nursery. This is shown in Figure 4.1. During winter house 47 meets category II 80-90% of the time. In this case the living room reveals the poorest results. The results from the living room are shown in Figure 4.2.

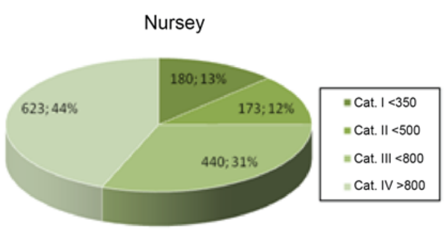


Figure 4.1: Hour distribution in comfort classes for winter situation in nursery in 2011, house 39.

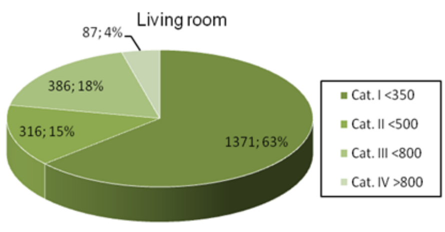


Figure 4.2: Hour distribution in comfort classes for winter situation in living room in 2010, house 47.

Category II is achieved 75-80% of the time in house 12, which uses the same air flow to ventilate the house as house 47. Assessing the air flows for these two houses, they differ in their methods of ventilation. The air flow is almost the same throughout the year in house 12; in house 47 the air flow changes depending on the season. This is evident in Figure 4.3; the red line indicates the air flow. Furthermore, the CO_2 level is clearly affected: it drops when the air flow increases.

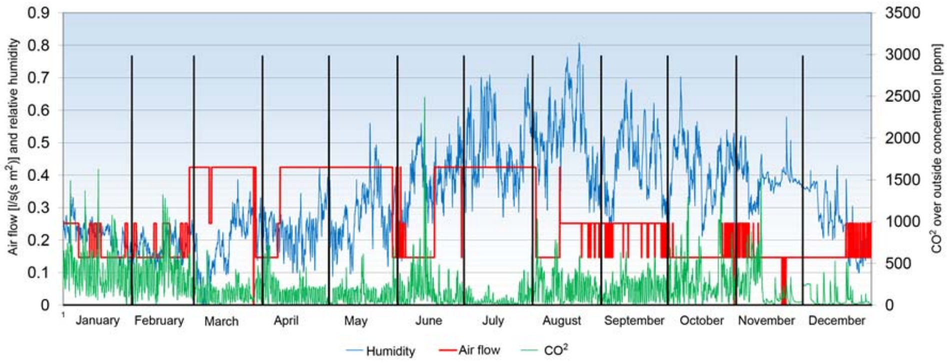


Figure 4.3: Air flow, CO_2 and humidity in living room, house 47, 2010.

Assessments of the CO_2 level on an annual basis recommend that transgressions occur only 3 or 5% of the time (cf. Appendix A: 'Indoor environment and energy consumption requirements'). The transgressions by the three houses mentioned are presented in Table 4.5. House 47 achieves the best results in 2011 with 0 and 1% in the kitchen-dining area and living room, respectively. House 12 shows slightly larger deviations and fails to achieve the desired 3 or 5%. This happens regardless of the fact that the air flow per person in this house is the highest; however, as the rooms in the east end of the house are not used every day, the house volume is in fact smaller. House 39 shows great deviation in the nursery, which only manages to meet category II approximately half the time in 2011.

	2009	**2010**	**2011**
House 12			
Kitchen-dining area	16	9	13
Nursery	15	9	14
House 47			
Kitchen-dining area	3	3	1
Living room	8	10	0
Bedroom	2	3	4
House 39			
Nursery	-	23	47
Living room	-	19	16

Table 4.5: Transgressions of category II on an annual basis.

4.5 Relative humidity

As with the CO_2 level, the relative humidity in the houses depends on the internal load in the form of people and the amount of ventilation. In addition, the behaviour of the residents in terms of shower and cooking habits and the drying of clothes inside the house will affect the relative humidity.

The houses that have the highest air change experience no or few problems with a high RH level; however, during winter and spring, the air in the houses is very dry.

Houses with a low air change experience problems with high RH levels for a good part of the year. In late summer, which is the period with the highest RH figures, the house values often exceed 70%, which can cause problems in the construction. In these houses problems with a dry indoor environment during winter are reduced, at the expense of a high CO_2 level, though.

In addition, bedrooms that are directly connected to a bathroom have proven problematic. These rooms often have a high RH level, reducing the quality of the indoor environment in the bedroom. This is evident, among other things, in Figure 4.4 for house 45, which meets category II approximately 41% of the time. A distribution in terms of measured RH values (cf. Figure 4.5) show RH>70% a large part of the time.

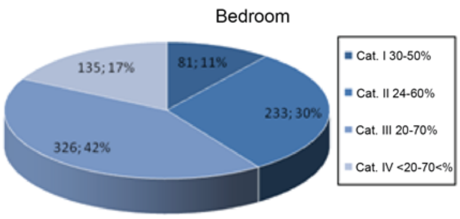


Figure 4.4: Hour distribution in comfort classes for autumn period in bedroom in 2011, house 45.

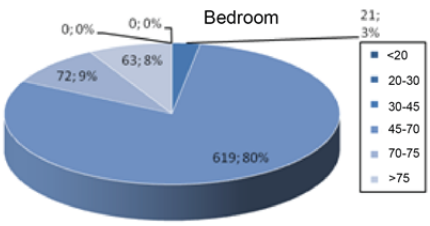


Figure 4.5: Distribution for measured RH for autumn period in bedroom in 2011, house 45.

Assessment of the criterion of RH<45% a minimum of 1 month, to avoid problems with house dust mites, shows that all the houses meet the criterion.

4.6 Summary

Everything indicates that future houses will be gradually larger and, at the same time, fewer people will be living in them. That is, a larger number of m² are available per person, which at the same time entails that the need for fresh air per m² is reduced – at least when the parameters temperature, CO_2 and humidity are taken into account.

Previously, the amount of ventilation per m² had to meet a set minimum requirement [BR08, BR10], but as the demand has decreased, on account of the above, it should be considered to which extent this requirement should be upheld or whether a reduction and thus a degree of energy conservation should be allowed. On the basis of this line of thinking the Comfort Houses were granted exemption from BR08 and were thus allowed to fit the houses with demand-controlled ventilation.

This chapter has presented the results from the 8 houses. All houses operate with smaller air flows than recommended in BR08/BR10. Some do so successful and still manage to achieve a healthy indoor environment; however, the houses with the lowest air change experience problems with a poor atmospheric indoor environment.

Assessments of the atmospheric indoor environment consider the houses' CO_2 level and relative humidity. CO_2 levels vary from house to house, depending on the air flow; assessments show that in some living rooms category II is violated between 0 and 19% of the time. However, most living rooms show minor violations. In the rooms the violations are more considerable, as there is a greater load per m² in these rooms for a longer period of time. Assessments show that some of these rooms violate the standards nearly half the time.

Assessment of the relative humidity shows that only few houses are able to meet the assessment criterion of a 3 or 5% deviation from category II. The violations are caused by low RH values which occur in winter. Most houses do not have problems with high RH levels. There is a tendency however to increased RH values in bedrooms in direct connection with a bathroom, as the humidity from the bathroom spreads and is not exhausted as it should be. All houses have periods of at least 1 month with RH<45%, just as there are no problems at the other end of the scale with RH>75%.

Considering the winter months which are often the most critical, all houses reveal an increased CO_2 level, as natural ventilation of the house is reduced. The level is not critical for the atmospheric indoor environment in the houses that operate with a high air change (0.24 l/s per m²). None of the systems installed register the houses' CO_2 levels, but if demand-control with air change rates that are significantly smaller than 0.5 h^{-1} is allowed in the future, it should be considered whether the additional investment is necessary. In addition, experience from the Comfort Houses shows that it is important to ensure a good air change in small rooms with a high internal load. As mentioned above, this includes bedrooms and nurseries where the load during the night is considerable. In some cases, nurseries are especially critical, as there is also a daytime load in these rooms.

5. Daylight

The tender documents do not refer directly to daylight conditions. However, they do say that 'The house must be functional and radiate comfort and wellbeing'. Seeing as the house design must include comfort, in this analysis good daylight conditions are also considered an element of comfort. The question remains, though, how good daylight conditions are defined. This problem will be discussed in this section alongside examples of how the daylight quality in the houses is increased. In additions, this section evaluates how the energy consumption is affected by the size and orientation of the windows and whether there is a connection between the daylight factor and the window/floor space and overheating.

5.1 Assessment criteria

In the Comfort Houses a minimum value of 2% for the daylight factor is used which should be obtained throughout a given room and not merely in areas considered workspaces. If this is met, the daylight conditions are considered good. In this way the depth of the room could also be included in the assessment, as deep rooms should have larger or higher window sections than narrow rooms.

5.2 General experience

Previously, the energy consumption for lighting has not been included in energy calculations for homes. Studies show that the consumption for lighting in homes correspond to approximately 7-10% of the total energy consumption in a standard home today [Marsh, 2008] [Gram-Hanssen, 2005]; however, as the energy consumption for heating and building operation now is decreasing, the electricity consumption's share of the total energy consumption will gradually increase.

Increased use of daylight in homes also entail, in addition to a reduction in the energy consumption for electricity for lighting, qualitative aspects – aesthetic, experience, health and comfort improvements – which have not been included here.

The amount of daylight in a room depends on the space and the position of windows in the facade and the roof, but it should also be balanced and controlled with solar shading with regard to direct solar radiation, as there is often a tendency in low energy houses to a massive overrepresentation of south facing windows and a severely reduced window area in north facing rooms. This may result in dark rooms in the northern part of the house as well as a risk of overheating, glare and stark contrasts in south facing rooms, if there is no clear solar shading strategy. At the same time, theopen facades can in close urban areas cause insight problems and thus inadvertent use of solar shading if the residents, in periods when solar radiation is useful, use solar shading to cover the rooms to thus reduce the possibility of looking into the house – this was a problem in Home for Life [VKR, 2010].

5.2.1 Case study: Daylight optimisation in a home

The following case study describes the daylight conditions in Home for Life built in 2009 in Lystrup near Aarhus, Denmark. It is a 190 m² two-storey house. The structure of the house is presented in Figure 5.1.

The design of the house has deliberately taken the daylightinto account. There is in the design worked with a relatively large overall window area, 40% of the floor area, approximately twice that of a normal single-family house.

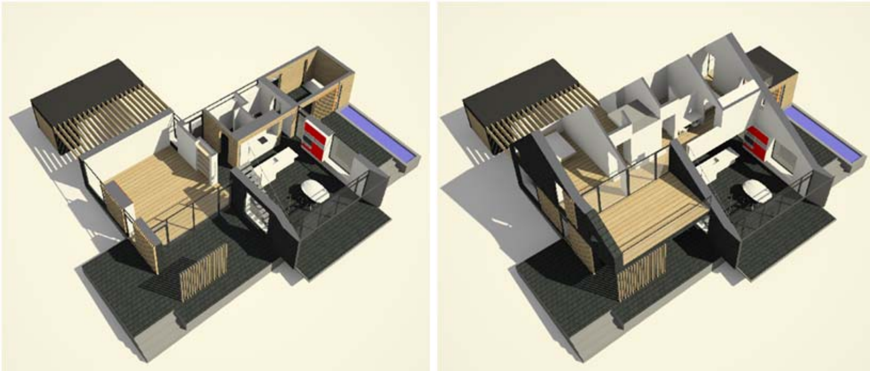


Figure 5.1. Structure of the house [VKR, 2010].

The design parameters for the house included the requirement that daylight should be able to light up the rooms to underline the architecture and generate a comfortable and practical light. One of the means hereto is that all the rooms have daylight coming from at least two directions. This minimises glare and increases the daylight factorwhich may replace the use of artificial lighting. Moreover, the design focused on producing a sufficient work and function light at the kitchen counter and in the work space in the bedroom to the east on the first floor. Calculations of daylight factors in these areas have found values of 6.7% and 4.3%, respectively. The goal in Home for Life was an average daylight factor of 5%. In addition to focusing on good daylight conditions, the design of the house focused on using energy-efficient light fixtures as well as artificial light control that turns the lights off when people leave a room.

5.3 Daylight conditions in the Comfort Houses

The assessment of the daylight conditions in the Comfort Houses took basis in the daylight factor in all living rooms/primary rooms. In addition, assessments of a few houses also included rooms with small windows in order to see the effect of small window areas on the daylight factor.

All primary rooms in the Comfort Houses are able to meet the requirement of a daylight factor of 2% at the back wall of a room. The results differ considerably, though, as some houses just manage to fulfil the 2% and other houses obtain values of as much as 6%.

To ensure a good daylight distribution in homes it is important to take the position of the windows into consideration. The following will present a number of examples from the Comfort Houses of good effects. Further examples can, among other places, be found in SBi 219 [2008].

5.3.1 High-placed windows and skylights

In houses 28 and 39 high-placed windows have been used to increase the daylight factor in the living room. A high-placed window in the external wall is able to increase the amount of daylight far into the room and it can in some cases ease the interior decoration of the room, as it creates more free wall space. Figure 5.2 and Figure 5.3 show the position of the windows in the living room in house 28. In this house, a high-placed window is positioned at the top of a wall to thus make it possible to furnish the corner and still ensure good daylight conditions in the room.

Figure 5.2: Position of windows in facade, house 28.

Figure 5.3: The effect of the window from inside the living room.

Measurements of the daylight factor in the living room registered three DF lines into the living room. The measurement points are evident in Figure 5.4. In line A which ends in the middle of the house in front of the kitchen showed a DF of just below 2%, which is a good result for a point that far into the house. The measurements are outlined in Figure 5.5.

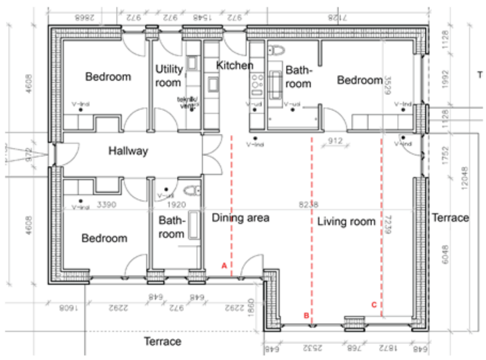


Figure 5.4: Position of measurement points in house 28.

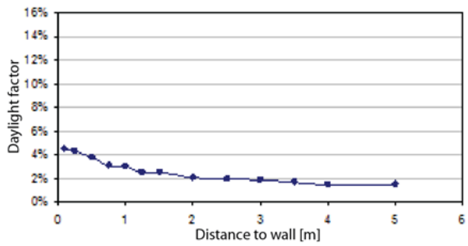


Figure 5.5: Daylight factor measurements in the middle of the house, point A.

House 39 also has a high-placed window. This window has been placed in connection with other windows. The position of this window is shown in Figure 5.6. Figure 5.7 presents a photo taken from inside the living room. With this relatively large glass area in the south facing facade it is important to ensure good external solar shading opportunities; if not, there is a great risk of excessive temperatures in the house.

Figure 5.6: Position of windows in facade, house 39.

Figure 5.7: The effect of the window seen from the living room.

In house 39 two DF lines were measured in the living room. In line A, which starts at the window section with the high-placed window, a DF of 6% was registered at the back wall, which gives a good and well-lit room.

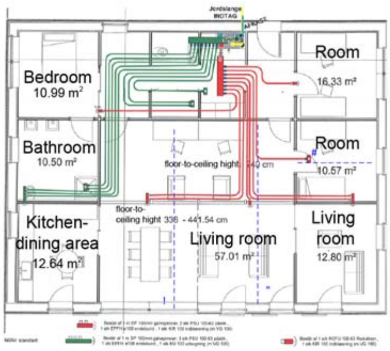


Figure 5.8: Position of measuring points in house 39.

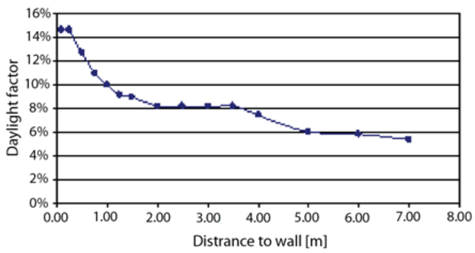


Figure 5.9: Measurements of daylight factor in front of the high-placed window, point A.

Figure 5.10: Skylight in house 49.

The figure below shows an example of the use of a skylight in house 49. The skylight can contribute with daylight in e.g. deep rooms and other areas where light from normal vertical windows may have difficulties reaching. In addition, if the skylight can be opened it can increase the effect of natural ventilation. A potential disadvantage of skylights with no solar shading is the extensive solar radiation via the window due to its horizontal position. Therefore, it is necessary to ensure some form of shading, at best in the form of an external shading or shudder or, on the inside, in the form of curtains or venetian blinds.

5.3.2 Light from multiple directions

Figure 5.11 shows an example of the use of light coming from more than one direction in house 47. In this house, however, the window sections are very large, and it is therefore important to control the risk of excessive temperatures and ensure good external solar shading.

Figure 5.11: South and east facing windows in house 47.

5.3.3 Use of interior glass for transport of light between rooms

In addition to the position of windows in the facade, interior glass is another option which may help distribute the daylight with great effect. Figure 5.12 shows two examples hereof. On the photo to the left (Figure 5.12a) glass has been fitted above the concrete core in house 37. The core includes a bath, toilet and utility room, and via the glass daylight is also transported into these areas. In Figure 5.12b (which is not from the Comfort Houses, but from Home for Life) a window has been fitted between the dining area and the nursery on the first floor which, at the same time, gives a view through the first floor skylight.

a.) **b.)**

Figure 5.12. Use of glass inside the house for transporting daylight.

5.4 Problems with dark rooms

Even though there are many good solutions with regard to the daylight conditions in the Comfort Houses, some of the houses also have problems with dark rooms. Dark rooms typically include rooms with very small windows. Examples hereof are e.g. found in houses 39 and 43; both have rooms with a DF of about 0.5% at the back wall. Measurements from these rooms and photos of the windows' position in the facades are presented in Figures 5.13 to 5.16.

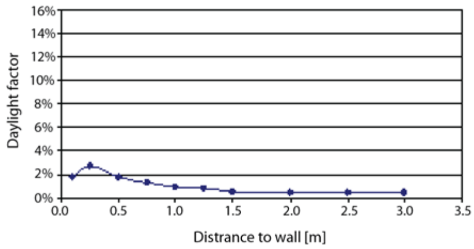


Figure 5.13: Measurement of the daylight factor in east facing room, point C, house 39.

Figure 5.14: Windows in east facade, house 39. Measurements made in room behind the window in the middle in the east facade.

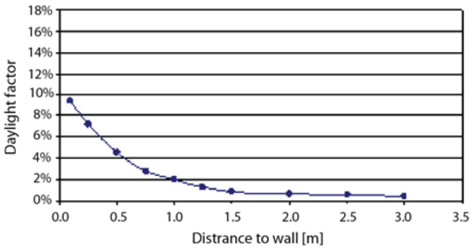


Figure 5.15: Measurement of daylight factor in north facing room, point B, house 43.

Figure 5.16: Windows in north facade, house 43. Measurements are made in room behind the window on the first floor furthest to the east.

From the beginning, the Comfort House project has focused on large south facing window sections and significantly smaller spaces in other directions – with regard to the energy balance. This focus may have resulted in dark rooms in some of the houses. In the course of the project the large window sections, in addition to plenty of daylight, also turned out to result in excessive temperatures in a number of houses. The idea of a more equal distribution of windows was therefore examined in the Comfort House book [The Comfort Houses: erfaringer, 2010], which showed that this is perfectly realisable. The advantages hereof are discussed in section 5.6.

5.5 Connection between DF, window areas and excessive temperatures

The building class 2020 in the building regulations includes a requirement for the share of windows in living rooms and kitchens-dining areas. The window area must be at least 15% of the floor space, if the light transmittance of the window is more than 0.75 [BR2010, 2012].

Table 5.1 presents an analysis that encompasses all eight Comfort Houses. For the rooms in which room temperatures were measured, the window area is compared to the floor area. These figures are then compared to set requirements for class II regarding the thermal indoor environment, which allows a deviation of 12 or 25%. The figures are from the month in which each house showed the greatest deviation.

It is evident here that some of the houses meet the building class 2020 requirements in all rooms, and others fail to. Houses 43 and 47 each have more than one room below the given 15%, but they also have rooms with a significantly larger share of windows. Most houses have relatively high figures compared to the 2020 requirements.

House no.	12	28	37	39	43	45	47	49
Living room		0,35	1,15	0,35	0,37	0,99	0,22	0,29
Kitchen-dining area	0,35				0,12	0,79	0,21	0,25
Bedroom	0,23				0,12	0,08	0,12	0,22
Room	0,30	0,24	0,21	0,14	0,10	0,48		0,22
Multi room					0,61			
Bathroom						0,34	0,06	
Office/corridor							0,28	

Table 5.1: Window/floor area in all rooms in which indoor environment measurements are made. Green figures represent a deviation in the thermal indoor environment from class II of less than 12%; black represents a deviation between 12% and 25%; and red represents figures above 25%. The grey areas indicate in which rooms the daylight factor was measured.

Assessments of excessive temperatures show no direct connection between window area/floor area and class II deviations, as this also depends to a great extent on, among other things, solar shading. Only houses 43 and 45 contain rooms that only reveal a 12% and 25% deviation.

The data above is further used in an analysis that includes both the window area/floor area, daylight, excessive temperatures in rooms and orientation. This analysis can be found in Figure 5.17. The analysis includes only the rooms for which the daylight factor was measured. The used daylight factor is the value measured at the back wall, i.e. the wall furthest away from the window or windows.

Each data set is given a colour code which indicates whether the room has experienced problems with excessive temperatures in the measurement period (percentage of the time in which the temperature in the room is above 26°C, according to class II). However, only the worst excessive temperature month is included in the analysis, and temperature measurements are missing for four rooms for which the daylight factor is measured.

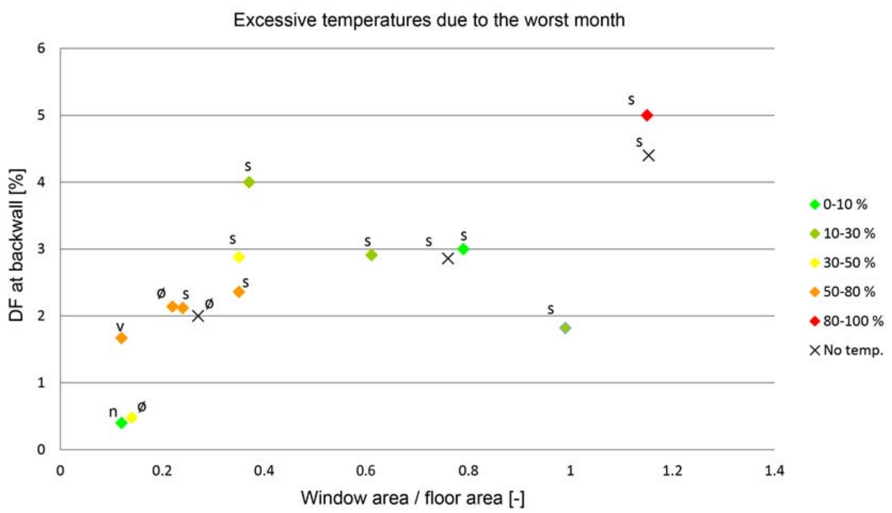


Figure 5.17: Daylight factor at the back wall as a function of the window area/floor area and share of excessive temperatures as well as the orientation is represented as colour code and corners of the world, respectively.

The figure reveals a connection between the window area/floor area and the daylight factor which is quite clear for a window area/floor area relation of as much as approximately 0.4. The rooms with larger deviation figures can be explained by the fact that many different factors affect the daylight conditions herein. One explanation could, as described in section 5.3.1, be the vertical position of the windows in the room, as high-placed windows provide a better daylight factor. Another issue could be the layout of the room in question.

Another obvious tendency is that all measured daylight factors above 2.1% are recorded in south facing rooms. This means that the largest windows have been placed on the south facade, which is also evident in the window area/floor area figures. It is evident in Table 5.1 that the data used in the figure and which give a value for window area/floor area of more than 0.3 are for living rooms and kitchens-dining areas. Observing this tendency it is important to ensure that it does not lead to thermal indoor environment problems; in this case several houses experience problems in the hot month that forms the basis for this analysis.

The value recommended in BR10 – 0.15 for window area/floor area in e.g. living rooms and kitchens-dining areas – is in this case not enough to ensure a daylight factor of more than 2% at the back wall of a room. In addition, it is important to remember that the position of the windows and the layout of the room are important factors.

Based on data from this project the 0.15 value should be changed to 0.2 to ensure a sufficient daylight factor. Subsequently, it is important to ensure that the critical living rooms in the building do not experience excessive temperatures.

5.6 Robustness with regard to the rotation of the building

Many low energy houses have significantly larger window areas in south facing facades than in north facing facades. This entails that the building is more dependent on being placed correctly on the building site. In addition, this design reduces the opportunity of reproducing the same ground plan (e.g. in connection with standard houses), as the house must be oriented towards the south. If the building design had an equal distribution of windows in all directions, it would have been possible to rotate the building and move it around in all directions.

This will be analysed below in connection with three different houses. The distribution of windows in the houses towards the north, east, south and west, respectively, is presented in Figure 5.18. It is evident that for house I (house 28) a very large part of the windows are south facing, while house II (house 37) has a more equal distribution of windows, and the windows in house III (house 43) are largely south facing and no windows are east facing

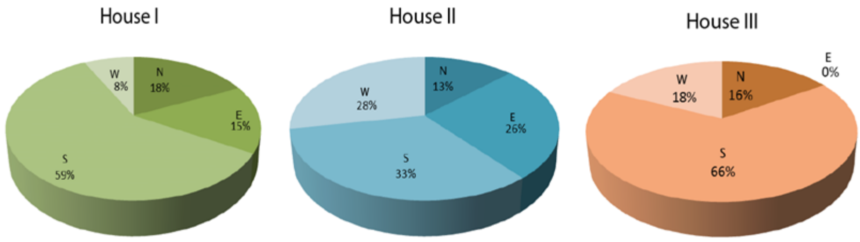


Figure 5.18. Distribution of window area towards the north, east, south and west, respectively, for three different houses [The Comfort Houses: erfaringer, 2010].

Below, the space heating demand as a function of the orientation of the house is analysed. In the analysis all three houses, regardless of their actual position on the site, have been turned in the calculation, so that they start with the south facade and are subsequently turned in intervals of 11 degrees towards east and west, respectively.

The result of the analysis is presented in Figure 5.19. It is not surprising that house II, with the most equal distribution of windows, is the less sensitive to being turned to face the corners of the world. House I which has a significant east facing window area and only a relatively small amount of west facing windows is the most sensitive to being turned towards the west. This analysis suggests that a certain amount of east facing windows especially are important to avoid this degree of sensitivity.

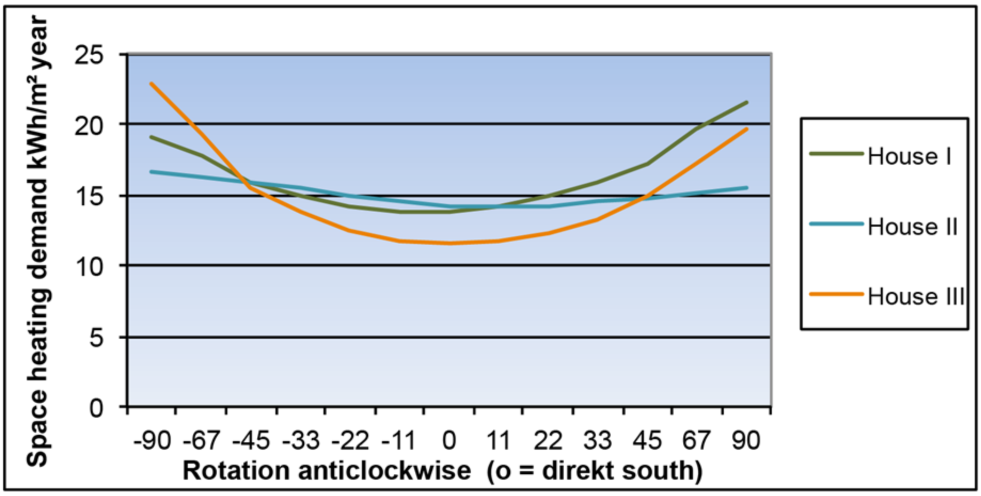


Figure 5.19. The space heating demand as a function of the orientation of the house compared to a southern orientation for three different window distributions [The Comfort Houses: erfaringer, 2010].

5.7 Summary

This section has discussed whether a daylight factor requirement should be included in the design of future low energy houses. The argument for doing so is that increased focus on the use of daylight in houses may at the same time ensure reduced energy consumption for electrical lighting and thus a cost reduction.

This section will provide two possible assessments of the daylight conditions in a house. One of these was used in the Comfort Houses, in which the criterion for good daylight conditions is a daylight factor of 2% at the back wall of a room, thus including the depth of the room in the assessment. The second method was used in Home for Life which seeks to achieve a 5% daylight factor for a room.

The majority of the rooms in the Comfort Houses have good daylight conditions. The measurements provide a number of examples of how the position of the windows may improve the daylight conditions. It is pointed out, however, that for all south facing positions it is important to ensure that the room will not experienceproblems with excessive temperatures. This is illustrated in the following section in which concrete measurements of excessive temperatures are compared to the DF and window/floor area. The results hereof are also compared to BR10 recommendations: a window area/floor area factor of 0.15 is recommended for 2015 and 2020 constructions. Based on experience from the Comfort Houses, a factor of 0.20 may be better.

Finally, the significance of the orientation of the windows with regard to energy requirement and robustness to the rotation of the building is analysed. Not surprisingly, the building with the more equal distribution of windows in all directions proved to be the most robust and could thus be placed on any building site regardless of its orientation. At the same time, a more homogeneous position of the windows in all directions could help prevent the problem with dark rooms in the northern part of the house as well as the risk of overheating, glare and stark contrasts in south facing rooms.

6. Acoustics and noise

Increased density and insulation in low energy houses also work as soundproofing against noise coming from outside the house and, therefore, sounds from installations inside the house may seem higher and more annoying. E.g. radiator valves may wail, taps and cisterns may make a whistling sound and the ventilation system will buzz. Additionally, all the Comfort Houses are fitted with mechanical ventilation which may also produce various noises if they are not fitted properly. The following outlines the results from the Comfort Houses which have been examined for noises from building services and reverberation times.

6.1 Assessment criteria

Table 6.1 presents the criteria that the acoustics measurements will be compared to. Both noise from building services and reverberation times must meet category B. This means that reverberation times must be <0.6 seconds and noise from building services must be less than 25 dB.

Acoustics and noise	
	Criteria
Reverberation time	Cat B
Building services	Cat B

Table 6.1: Criteria for assessment of the acoustic indoor environment.

6.2 Reverberation times

A number of different efforts have been made in the Comfort Houses to ensure low reverberation times. The different solutions are presented in Table 6.2. It is evident from the table that none of the houses are able to meet category B. In that connection, it is imperative to mention that reverberation times must be measured in furnished rooms; this has not been possible in this project. The measured reverberation times can still be used, however, as an indication of the houses in which the residents must be particularly attentive to lowering the reverberation times; as interviews with the residents revealed problems in one of the houses with high reverberation times.

Below is an example from a resident interview. The interview is conducted by Camilla Brunsgaard [2010] and the quotation is that of the resident on the subject of noise and acoustics:

> Quotation: ‘Sound travels more easily than anywhere else I have ever lived. Listen to this, that room up there, if someone farts, you can hear it as far away as in the living room. And vice versa. It is crazy. If I need to talk to someone upstairs, I can sit down here and talk, they can hear that. It is very bad, so bad. All these plates … they don’t work … they have never worked … The reverberation here – well, you can almost hear it now. I mean even though we have pictures on the walls, flowers, which can break the acoustics, they don’t break anything. No, it doesn’t break the acoustics …’ (Our translation)

	12	**28**	**37**	**39**
Average reverberation times (125-4000 Hz) **WITHOUT FURNITURES**	1,23	0,89	0,79	1,34
Initiatives to change the acoustics	Shiplay boards 	Cement-bonded wood wool, rising floor-to-ceiling height 	Rockidan, mineral wool with acoustics plaster 	No sepcial initiatives. Varying floor-to-ceiling height 
	43	**45**	**47**	**49**
Average reverberation times (125-4000 Hz) **WITHOUT FURNITURES**	1,13	0,86	1,4	1,4
Initiatives to change the acoustics	Acoustic regulation in internal wall. Perforated plaster board from Gyproc 	EXPAN sound deck – acoustic deck underside and architectur e with varying floor-to-ceiling height. 	Areas with perforated plaster boards from Gyproc 	No special initiatives. 

Table 6.2: Average reverberation times and an overview of initiatives to control the acoustics.

6.3 Noise from building services

The measurements made in the Comfort Houses included measurements of the noise from the ventilation system on the expected daily operation level. For this measurement all the houses met sound class C; the majority also met sound class B, corresponding to 25 dB.

The measurements were combined with a subsequent qualitative assessment via interviews with the residents [Brunsgaard, 2010]. Several interviews revealed that the ventilation systems are noisy when they operate with air flows that exceed the standard operation level. I.e. in these examples noise above 25 dB annoyed the residents, despite the fact that the sound class B requirement was met.

In connection with noise from building services it is important to emphasise that the position of the ventilation system and noise screening around the system are important for achieving a good result in assessments of noise from the system. A possible solution could be to choose a soundproof door for the technical room as well as soundproofing for all system channels.

6.4 Summary

In a number of Comfort Houses initiatives have been made to ensure good acoustics. Measurements of reverberation times in unfurnished rooms revealed that the houses differ significantly in terms of soundproofing, and the average values vary from 0.79s to 1.4s. However, there is a clear difference between houses with acoustics control and houses without. With one exception, though: where acoustical ceilings fail to reduce the time of reverberation in double height rooms with numerous heavy constructions.

Noise from building services is measured at the ventilation system's standard operating level. The measurements revealed no problems with meeting category B (<25 dB) standards; however, interviews with the residents in some of the houses indicated that noise from the systems is a nuisance at higher air flows.

7. Energy consumption and energy efficiency

All the Comfort Houses are passive houses; this means that they should meet the passive house criteria listed in Table 7.1. PHPP calculations naturally show that all the houses do meet these criteria; however, via the measuring programme it is possible to determine whether the houses also meet the criteria in practice.

Space heating demand	15 kWh/m² pr year
Primary energy demand	120 kWh/m² pr year
Airtightness	0,6 h^{-1} v. ΔP = 50 Pa

Table 7.1: The passive house criteria [PHPP 2007].

Seeing as the PHPP calculation is based on a series of preconditions (e.g. a room temperature of 20°C, a standard outdoor climate and a given internal load), it is not possible to compare the measured and calculated values directly. Instead, a new PHPP calculation must be made, which includes the measured weather data. Consequently, the expected energy consumption can be compared to the measured consumption. An illustration of the importance of using correct weather data can be found in Appendix E: 'Comparison of weather data (DRY & Skibet)'. A comparison of weather data from Skibet and weather data from Billund can be found in Appendix F: 'Comparison of weather data (DMI-Billund & Skibet)'. This comparison is made, as weather data for Billund is used in PHPP.

In order to make the most reliable comparison between the measured and calculated energy consumption, the houses must be inhabited at the time of comparison. As most of the houses were not inhabited for one consecutive year with useable data, an 'artificial' year has been generated for all houses. This year is used both to determine the measured energy consumption and to produce a set of measured weather data. The artificial year is made up of different months selected in the course of the measuring period. In addition to energy consumption, the PHPP calculation with weather data from the artificial year is also used to assess problems with excessive temperatures.

No energy consumption data has been included for house 45, as the resident, upon moving into the house, switched off the project's internet access to the house. Therefore, the only measurements that exist for house 45 were made using wireless access – i.e. indoor environment measurements.

7.1 Assessment of energy consumption for space heating

Assessing the space heating requirement < 15 kWh/m² a year, all the houses' room heat sources are determined. These are summarised and converted to annual values, which are comparable to the PHPP result. As several houses revealed a room temperature in the heating season that deviated from 20°C, the figures below have been adjusted accordingly. It is the value for this adjustment that is compared to the measured value. The results of this comparison can be found in Table 7.2.

	12	28	37	39	43***	45****	47	49
Energy consumption in PHPP with standard weather data	15	15	14	15	12	-	13	15
Energy consumption calculated in PHPP with artificial year	24	23	23	23	25	-	20	23
Average temperature in the heating season	23,0	23,5	24,0	23,0	22,4	-	22,3	23,0
Energy consumption calculated in PHPP with the artificial year + corrected indoor temperature	31	32	32	31	31	-	26	29
Measured energy consumption	**33**	**28***	**17****	**27**	**34**	**-**	**55**	**28**

*** Energy given to two electric radiators is not included. Actual consumption will be higher.**
**** Energy to electric radiator + energy to radiator linked to geothermal heat pump is not included. Actual consumption will be higher.**
***** Estimated data have been used due to lack of data.**
**** Lack of data, cf. introduction.

Table 7.2: calculated and measured energy consumption. All energy consumption values are given in kWh/m² a year. The average temperature is given in °C.

It is evident from the results in Table 7.2 that for most of the houses the calculated energy consumption is in good keeping with the measured energy consumption, and all the houses, except houses 45 and 47, meet the passive house criteria. However, the consumption in houses 28 and 37 will in practice be higher than the measured values, as additional heat sources have been added to these houses, due to insufficient heating, and not been connected to the measurers. However, their contribution is considered less extensive.

The only house that fails to meet the passive house requirement is house 47; its energy consumption deviates significantly from the other houses' energy consumption. The energy consumption in this house is approximately twice the calculated consumption for this house. The problems registered in the house may help explain the deviation, at least partially. A water-based pre-heating surface burst due to frost and was replaced by an electrical heating coil. In this connection and during subsequent service, the service technician, due to lack of knowledge of the design of the system, made a number of undesirable changes to the system, both with regard to the automatic control and the layout of the system. Therefore, the system has not operated in the optimum way and was not returned to its original design until after the end of the project.

7.2 Assessment of primary energy consumption

As with the space heating requirement, the primary energy consumption is evaluated on the basis of a PHPP calculation with weather data from the artificial year and adjustments for measured indoor temperatures in the heating season. Some of the calculations do not provide a result after adjustment, but it is assumed that the size of the increase will follow the houses that did provide a result. The results of the comparison can be found in Table 7.3.

	12	**28**	**37**	**39**	**43**	**45****	**47**	**49**
Primary energy consumption calculated in PHPP with standard weather data	91	119	120	120	100	120	92	114
Primary energy consumption calculated in PHPP with artificial year	96	134	133	133	109	-	99	-
Primary energy consumption calculated in PHPP with artificial year + corrected indoor temperature	101	153	-	-	113	-	105	-
Measured energy consumption	**123**	**162***	**132**	**138**	**86,4**	**-**	**262**	**211**

*** Exceeded due to** connected electric radiatiors in the house
** Lack of data, cf. introduction.

Table 7.3: Calculated and measured primary energy consumption. All values are given in kWh/m² a year.

As evident from the comparison in Table 7.3, the measured electricity consumption varies significantly: there is a factor 3 in difference between the highest and lowest consumption. Houses 12, 37, 39 and 43 meet the passive house criterion. House 28 reveals a 9 kWh deviation which is likely to disappear if the electrical radiators in the house are replaced with a heat source that is connected to the house's geothermal heat pump.

Houses 47 and 49 both violate the criterion to a significant extent, though. The explanation for the violation in house 47 was given in the previous section. In house 49 the problem is similarly of a technical nature. In this house the pre-heating surface was in connection with a power cut in October 2009 cooled to such an extent that the system was switched off to prevent frost bursts. In order to subsequently accelerate the heating, the service technician changed the control, giving the electrical heating element in the hot-water tank, not the heat pump, first priority in the system. In addition to domestic hot water, the hot-water tank supplies the floor heating in the bathroom and the radiator in the living room with hot water. This error was not corrected until the end of the summer 2011. Until then the electricity consumption was high.

7.3 Assessment of the airtightness of the houses

A blower door test was conducted for all houses. The results of these tests are provided in Table 7.4.

	12	28	37	39	43	45	47	49
Measured airtightness by blower door test compared to the PHI demand on 0.6h^{-1} at ΔP = 50Pa	0,59	0,50	0,42	0,40	0,60	0,40	0,50	0,30
Measured airtightness by blower door test compared to the BR08 demand on 1.5 l/s pr m² at ΔP = 50 Pa	0,33	0,27	0,30	0,21	0,34	0,21	0,35	0,16

Table 7.4: Result of blower door test. All values are given in h^{-1} for PHI requirements (at the top) and l/s per m² for BR08 requirements (at the bottom).

It is evident from the test results that all houses meet the airtightness requirement. Furthermore, it is evident how great a difference there is between the BR08 requirements and the measured values from the Comfort Houses. The effect of airtightness on the energy consumption is discussed in section 3.6.

7.4 Assessment of PHI recommendation of a maximum of 10% excessive temperatures (t > 25°C)

Section 3.3 addressed the problem with excessive temperatures in the Comfort Houses, which in some of the houses resulted in a poor thermal indoor environment. The following evaluates the criterion of temperatures above 25°C a maximum of 10% of the time. In this case the figures have also been adjusted to accommodate weather data from the artificial year. The results are evident from Table 7.5.

	12	28	37	39	43	45	47	49
Expected time with excessive temperature calculated in PHPP with standard weather data	4	3	0	0	0	0	3	1
Expected time with excessive temperature calculated in PHPP with artificial year	3	3	1	0	0	-	4	0
Measured from figures in artificial year (average for all rooms)	12	21	32	4	17	6	16	6

Table 7.5: Control of the passive house recommendation of a maximum of 10% excessive temperatures.

It is evident from Table 7.5 that 5 out of 8 houses have problems with excessive temperatures more than 10% of the time. This tendency is also confirmed by the assessment of the thermal indoor environment in chapter 3.

It is important to stress that excessive temperature calculations are based on an average temperature in the entire house that is inconsistent with the indoor environment in a real house. E.g. the average value of 17% in house 43 encompasses a violation of up to 22% in the first floor living room and a 9% violation in the northeast nursery. Thus, in reality, the rooms vary, but this variation is not included in the assessment of the building as a whole. This issue has also been examined in Larsen [2011], who recommends indoor environment control in critical rooms.

7.5 Energy efficiency (SFP, exchanger efficiency)

The assessment of the Comfort Houses' energy efficiency includes assessments of the energy for air transport in the system (the SFP value) and of the heat exchangers' efficiency. Both assessments contain a degree of uncertainty, as the air flow may change in the period. The air flows in all houses in the period from October 2008 to April 2009 have been measured, but have not been verified subsequently after the equipment was removed. The measurements were made at different operating levels. As house 43 operates with a stepless ventilator, a ventilator characteristic was made to determine the air flow in the house. This is evident in the house-specific report for house 43.

7.5.1 SFP value

Assessments of the measured SFP values for each house are outlined in Table 7.6.

	12	28	37	39	43	45	47	49
Measured SFP	364/ 463	2054/ 2088	1371/ 1368	618	1244	-	1548/ 997	629

Table 7.6: The SFP values measured in the houses. When two values are given, they correspond to family 1 and family 2, respectively.

It is evident from the table with the measured SFP values that the values differ significantly; there is a factor 6 difference between the highest and lowest values. Considering the impact hereof on the electricity consumption for the houses' ventilators, house 12 reveals an annual electricity consumption of 140 kWh. In house 28 this figure is 325 kWh. At the same time, it is important to remember that the air flow for house 12 is 0.24 l/s per m², but only 0.13 l/s per m² for house 28. Therefore, the air change in house 12 is significantly higher, whereas the electricity consumption is less than half of that of house 28.

Thus, a high SFP value can ruin even the best of intentions of making an efficient and energy-friendly ventilation system; therefore, one option could be, as a standard element upon delivery of the house, to document this on the basis of measurements of the system installed.

7.5.2 Exchanger efficiency

Before the project was launched it was discussed whether it was possible to determine the efficiency of the heat exchanger in the ventilation system, as these calculations must be very accurate with regard to the position of the sensors in the system. Naturally, a system in the 'field' does not provide the same level of accuracy as a system in the laboratory. The measurements were nevertheless conducted, and the conclusion is as expected that these measurements vary a lot in terms of quality. The measurements from the different systems used in the houses are presented below. The uncertainty of the measurements is expected to be about +/- 10%.

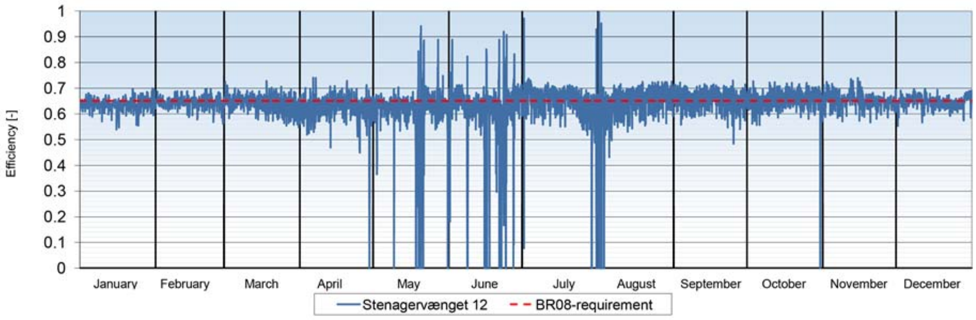


Figure 7.1: Efficiency measured in Stenagervænget 12, 2010. The uncertainty of the measurement is approximately +/- 10%.

Figure 7.1 shows the efficiency measured in the Drexel and Weiss system. The efficiency is stable, showing an annual value of 0.6.

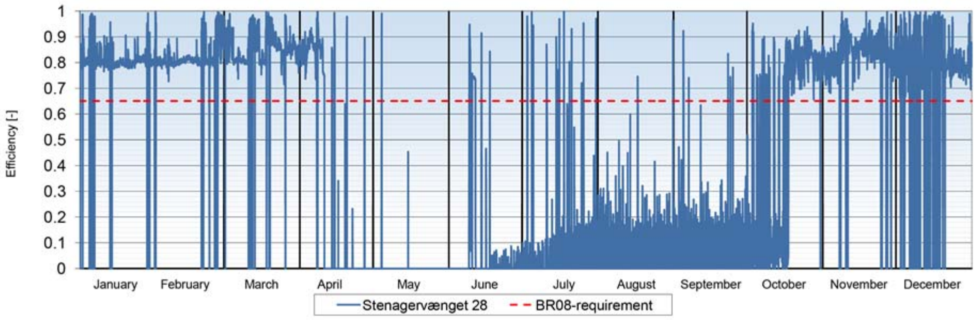


Figure 7.2: The efficiency measured in Stenagervænget 28, 2010. Uncertainty of the measurement is approximately +/- 10%.

Figure 7.2 presents the Nilan VP18 compact system measurement. Here the efficiency is approximately 0.8. The summer period is bypassed, which explains the lack of measurements in the summer period.

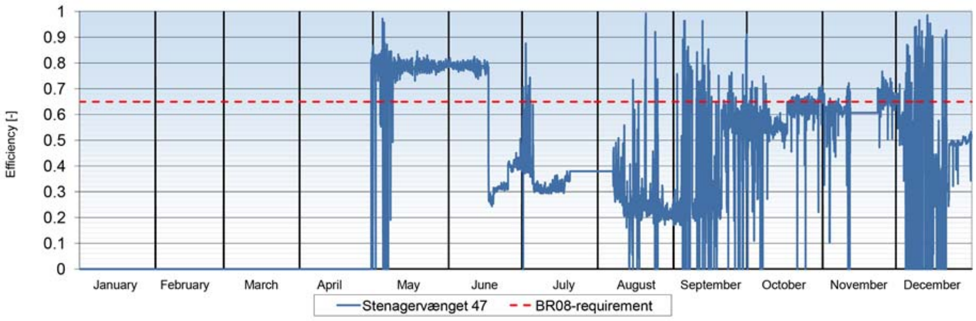


Figure 7.3: The efficiency measured in Stenagervænget 47, 2009. Uncertainty of the measurement is approximately +/- 10%.

Figure 7.3 shows measurements from the Nilan comfort 300 ventilation system. Here the efficiency oscillates between 0.8 and 0.4. Only between 0.6 and 0.8 in winter, though. The system is switched off in December, as the house is empty in this month.

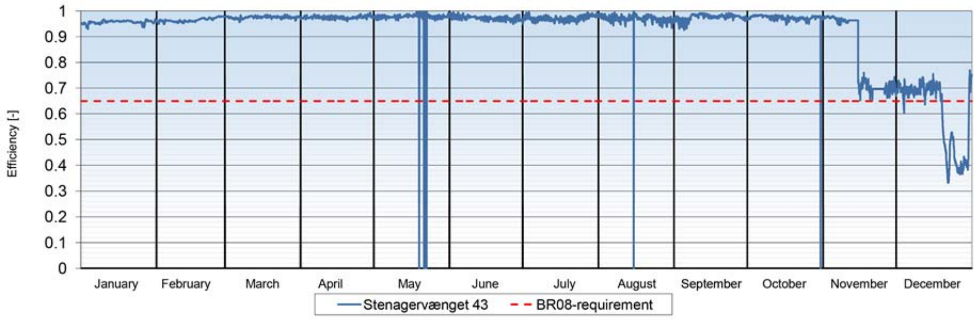


Figure 7.4: The efficiency measured in Stenagervænget 43, 2010. Uncertainty of the measurement is approximately +/- 10%.

Figure 7.4 presents measurements from the Paul Atmos 175 ventilation system installed in house 43. Most of the year the measurements reveal an unusually high level of efficiency; however, the data sheet for the system promises a 85-95% efficiency. The system has not been switched to bypass (must be done manually) which is consistent with the fact that the residents did not move in until August. In November the level drops, as the air flow changes.

7.6 Summary

All the Comfort Houses are passive houses; this means that they should meet the passive house criteria. This chapter has therefore controlled whether this was the case, comparing figures for calculated and measured energy consumption, respectively.

Seeing as the PHPP calculation is based on a series of preconditions (e.g. a room temperature of 20°C, a standard outdoor climate and a given internal load), it is not possible to compare the measured and calculated values directly. As both the outdoor climate and room temperatures are important parameters in energy consumption assessments, in the PHPP calculation both parameters were adjusted according to the measured values in the Comfort Houses. This resulted in almost a doubling of the calculated expected energy consumption, which clearly illustrated the importance of these two parameters. Most houses have operated with a temperature of approximately 23°C, which in this case costs an additional 6-8 kWh/m² a year.

Assessments of the *passive house space heating demand* show that all houses, except one, meet the passive house requirements. In practice, the consumption in houses 28 and 37 will however exceed the measured values, as additional heat sources were used in the houses on account of insufficient heating, but not connected to the project measurers. These contributions are nevertheless considered to be of a minor extent. Data for house 45 is missing and the house has therefore not been included in the assessment. The one house that deviates from the requirement experienced technical difficulties in the period in question which may explain part of the deviation.

Assessment of the *passive house primary energy demands* showed great variation in the measured electricity consumption and a factor of 3 between the highest and lowest consumption. Houses 12, 37, 39 and 43 meet the passive house requirement. House 28 shows a 9 kWh violation, which is likely to disappear if the electrical radiators in the house are replaced with a heat source that is connected to the house's geothermal heat pump. On the other hand, houses 47 and 49 both violate the requirement to a significant extent. Both houses have had technical difficulties which may explain part of the deviation.

Assessment of the *passive house excessive temperature demand* reveals that five out of eight houses struggle with excessive temperatures more than 10% of the time. In this connection it is emphasised that excessive temperatures are measured on the basis of an average temperature in the entire house which is not consistent with the indoor environment in a real home. In practice, the rooms in a house will vary significantly: a fact that has not been taken into account in the assessment of the building as a whole. Excessive temperature assessments should therefore be made for each room individually.

At the end of the chapter SFP values and the efficiency of the heat exchanger in the ventilation systems were evaluated. The SFP values show a factor 6 in difference between the highest and lowest values, which raises the question of whether documentation hereof should be a requirement upon delivery of the system. The efficiency of the systems is within the expected level.

8. Users' impact on energy consumption and indoor environment

The users' impact on the energy consumption as well as the indoor environment is an important factor in assessments of these parameters. Users' behaviour can mean a factor 3-4 variation in the energy consumption of the house [Andersen, 2009], [Gram-Hanssen, 2005], [Janson, 2010], and it is therefore important to consider whether the users can be effected, and thereby improve the indoor environment and at the same time reduce the energy consumption.

8.1 General experience

There is a lot to suggest that communication and informing the users is the road to success, and more than one example demonstrates how lack of information has led to either a poor indoor environment or increased energy consumption [Brunsgaard, 2010], [Janson, 2010].

An example hereof could be the residents' use and maintenance of the ventilation system. Most Danish families are not used to having a ventilation system in their homes and, therefore, a successful result and an energy-friendly performance require information and a change of behaviour. Based on experience from this and similar projects one might therefore consider whether the ventilation systems, just like our cars, should be subjected to regular service checks.

A number of examples of inexpedient behaviour were found in the Home for Life project which mentions the following [VKR, 2010]:

- The family has problems with overheating in the large south facing kitchen-dining area. The mother is on maternity leave and therefore at home most of the time. She often 'overrules' the external solar shading to be able to enjoy the view, which may be one of the reasons why the kitchen-dining area overheats.
- The family often overrules the automatic house control – especially in connection with heating and solar shading – to be able to enjoy the view and create a sense of privacy in the living rooms. Despite the many incidents hereof, the family is positive towards the automatic control.
- The family found the sound of the skylight windows opening during the night annoying, which made them switch off the automatic natural ventilation in the rooms during the night, thus reducing the option of night cooling.
- The house is ventilated via automatic natural ventilation and mechanical ventilation with heat recovery. When the natural ventilation was switched off in November, the family missed the fresh air and the sound of the windows opening automatically. They therefore started to air the house manually by opening windows and doors. This often led to a cooling of the house below 22°C at which point the heating system is switched on. Hence, this created an inadvertent increase in the energy consumption for heating.

Thus, there are numerous examples of the users 'working against' the best intentions of the technical equipment which is meant to help them achieve an optimal and energy-efficient house performance. Overruling the automatic control also shows that the residents need to be able to influence their indoor environment, and taking this option away from them by using automatic control only and thus optimum performance would displease the residents. Another option is therefore more information on how the house works and how residents should behave in order to achieve the highest energy efficiency and the best indoor environment.

8.2 Experience from the Comfort Houses

The first couple of years a number of behavioural conditions increased the Comfort House residents' energy expenses. Some problems were a result of ignorance; in other cases, the behaviour of the residents was not desirable from an energy economic viewpoint.

The following are examples from the project period:

- In house 12 the residents need to change the system from winter mode to summer mode manually by exchanging the exchanger module, which is responsible for heat recovery, with a bypass module. The residents forgot to do this the first two summers, which led to increased excessive temperature problems.
- In the same house family 2 prefers a temperature of 24°C in the living room during winter. This increased the energy consumption for heating significantly. The same is the true for some of the other houses.
- In houses 37 and 45 the residents air the houses for longer periods of time during winter. This cools the houses to an unnecessary extent and increases the systems' problems with heating the houses. Airing should instead have been done via the mechanical ventilation system.
- In house 45 in a cold period the residents placed a gas heater in the living room. This increased the CO_2 concentration in the house significantly and thus resulted in a poor indoor environment.
- In house 47 the residents did not want the house to smell of tobacco smoke when someone smoked indoors. Therefore, the ventilation system was often used for forced ventilation on a high (energy intensive) level.
- Several houses operated with very low air flows, as the residents mistakenly believed that by turning down the system they were able to save energy. Unfortunately, this had other consequences such as an increased CO_2 level, RH and energy consumption for heating from other heat sources.

Several of the examples above could have been avoided by providing the residents with more information on how to use their house and, at the same time, save energy. Of course, it will always be the individual user who decides whether the windows e.g. should be open in the bedroom during winter, but the users should be made aware of the cost in terms of energy of airing the house via the windows in winter instead of letting the ventilation system do it. In the same way, it is important to explain to the residents the advantages of opening the windows during summer and use the free cooling available in the air outside, especially during the night. This could potentially result in a long list, but one obvious idea in the future is to put this information into a house manual. Experience from the Comfort Houses suggests that this would have corrected some of the problems above.

8.3 Summary

In a Swedish study Isaksson concludes that the users did not buy their low energy homes because they were low energy homes, but because of their location and view. Their attitude to the low energy concept is positive, but it did not constitute an important reason for buying the house [Isaksson, 2006]. The same conclusion is found in [Brunsgaard, 2010], evaluating the Comfort Houses.

At the same time, Isaksson describes how some of the residents light candles and are very conscious of when they e.g. need to use the tumble drier to keep the house warm and make sure that all inner doors are open to allow the heat to spread around the house. Isaksson also mentions initiatives such as letting the bathwater cool in the bathtub before letting it out [2006]. In another study Janson explains that some users compensate for low indoor temperatures by putting on extra clothes before turning up the heat [2010].

Several of these examples place demands on the users to change their behaviour, compared to their previous homes. Not all are willing to make, or conscious of, this behavioural change, and it should also be discussed whether it should be necessary to change one's behaviour to live in a low energy house. Residents who do not have an 'energy-friendly' behaviour should also be able to live in low energy houses without it limiting their behaviour. Therefore, the residents' personal comfort should never be reduced – if this is necessary, the low energy concept will never become a success.

An obvious option in future low energy construction is to produce a manual for the residents. Not necessarily to change their behaviour, but to ensure that they understand the consequences of their behaviour which, in some cases, increases the energy consumption quite markedly.

9. Future low energy homes

The Comfort Houses started out as a development project – a project that would provide experience in low energy construction in a Danish context – a project that would produce new knowledge for the Danish construction industry. After monitoring the project via measurements made in the houses over a three-year period it is possible to conclude that the objective of the project has been fully fulfilled. In this chapter some of the major experiences from the project are outlined with a view to help future low energy construction a step on the way towards achieving an optimal balance between a good indoor environment and low energy consumption.

9.1 Indoor environment

Assessments of the indoor environment include the temperature, CO_2 level and relative humidity. With regard to the thermal indoor environment, excessive temperatures were the most discussed, as several houses had problems with this subject. With regard to the atmospheric indoor environment focus was on the high CO_2 levels and relative humidity levels in the nurseries and bedrooms at night.

On the basis of experience from the project the following areas require particular focus in order to achieve success:

- Opportunity of external solar shading
- Opportunity of the use of natural ventilation during summer (both day and night)
- Optimisation of daylight conditions, both to ensure good daylight conditions in ALL rooms and to prevent excessive temperatures
- Control of the indoor environment in critical rooms, including the following main focus points:
    - Thermal indoor environment in rooms with significant solar radiation to avoid overheating
    - Atmospheric indoor environment in bedrooms and nurseries to ensure a sufficient air change and to avoid high relative humidity or CO_2 levels
- A ventilation system with a CO_2 as well as a humidity sensor, if demand-control is required
- Humidity in bedrooms with direct access to bathrooms – there is a tendency to increased RH in these rooms. An exhaust device in the bathroom must be able to increase the air change when residents take a bath
- Cold bedrooms – if this is a wish on the part of the residents, they should be informed of the effect on the energy consumption of cooling one room in the house
- Soundproofing room with ventilation system – remember to take this into account to prevent noise from the ventilation system from spreading to the rest of the house

Furthermore, during winter there are problems with dry air. There is no immediate solution to this problem, as one solution would be dampening, which could cause other problems in the house.

9.2 Energy consumption

Nearly all the houses in this project managed to meet the energy consumption requirement. It is important to underline, though, that the design of future low energy homes should include a heating system with a surplus capacity. The energy calculation is based on standard conditions, but as shown in this project the space heating demand almost doubles as a result of a winter that is colder than the one represented in the standard weather data and a desired room temperature of 23°C. In some houses this caused problems with cold rooms, as the systems did not have a surplus capacity.

A summary of significant points in connection with the energy consumption of the houses might include the following:

- Make sure there is a surplus capacity in the house's heat supply – numerous parameters may deviate from the energy calculation. The most important include the outdoor climate, internal load and indoor temperatures.
- Use a form of windscreen at the front door, as it may help prevent great heat losses, when the door is opened in winter.
- Make sure that all rooms are directly connected to the heating system, thus reducing the risk of cold rooms significantly.

9.3 Dialogue with the users

The users in the homes represent a main success factor. Inexpedient user behaviour can ruin even the best of intentions of a good low energy house. Chapter 8 outlines a series of examples of how users can increase the energy consumption in the house significantly.

An obvious way to help the users develop energy-efficient behaviour is by producing a house manual. This manual could e.g. consist of a folder with all the papers for the house and an explanation of how the house works. To many people mechanical ventilation is still a new element in a home, and it is therefore important to explain how the system works and how it should be maintained. The guide could also include a DVD with illustrations/an outline of the house and its installations via which one can find more information on a subject that may be of particular interest at the moment in question. E.g. the DVD could contain a clip with a person changing the filter in the ventilation system, enabling the family to do the same.

Furthermore, it is also important that the technicians who service the systems have information/knowledge of how the systems and technical devices in the house work.

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Appendix A: Indoor environment and energy consumption requirements

Assessment of the measurements focuses on the thermal and atmospheric indoor environment, using the guidelines outlined in DS/EN 15251 (Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics). The project's original analyses from 2008 took as their starting point DS/EN/CR 1752, *Ventilation for buildings – Design criteria for the indoor environment*, but as DS/EN 15251 is used to a greater extent today the analyses in this report predominantly follow the latter standard; nevertheless, the assessments draw inspiration from various different sources for evaluating measurement results, as evident from the section below. The original draft for the assessment of the indoor environment is attached as Appendix A.

The Comfort Houses competition programme made no concrete demands as to compliance with a specific level; however, as the houses are marketed as Comfort Houses, they should as a minimum meet category II. This category corresponds to normal expectations and should be used in all new construction and renovation projects [DS/EN 15251, 2007]. The results of the measurements of temperature, relative humidity and CO_2 levels will therefore be considered with regard to whether or not they comply herewith. The requirements for the thermal and atmospheric comfort based on DS/EN 15251 are examined in sections A.1 and A.2. The requirements for the daylight factor in central rooms are examined in section A.3 and are based on BR08. Requirements for the acoustic indoor environment take as their starting point *DS490 Sound classification of dwellings,* and are examined in section A.4.

Assessments of the energy consumption in each building will both focus on different types of consumption and on whether or not the house meets the passive house criteria and the passive house recommendations. This is described in more detail in sections A.6 to A.8.

A.1 Thermal indoor environment

In order to be able to place a demand on the thermal indoor environment, a activity level must be assumed. 1.2 met was used, which corresponds to sedentary activity. Table A.0.1 presents temperature intervals for categories I, II and III to which the measurement data will be compared.

Activity level	[met]		1,2		
Category			I	II	III
Operative temperature	[°C]	Summer	24,5 ± 1,0	24,5 ± 1,5	24,5 ± 2,5
		Winter	22,0 ± 1,0	22,0 ± 2,0	22,0 ± 3,0

Table A.0.1. Temperature requirements for categories, I, II and III, respectively [DS/EN 15251, 2007].

When the project was launched in 2008 the building code did not specify any requirements for the thermal indoor environment; however, subsection 6.2.1, 1 did say that:

'Buildings must be constructed such that, under their intended operational conditions and at levels appropriate for the human activities to be carried out in them, comfortable, healthy temperatures can be maintained in the rooms occupied by any number of people for an extended period' [Br08].

The 2010 building regulations places demands on low energy class 2015 and building class 2020, specifying that the thermal indoor environment in critical rooms must be documented. Here the temperature may only rise above 26°C for 100 hours a year and above 27°C for 25 hours a year.

A.1.1 Criteria for complying with category

DS/EN 15251 introduces a method for evaluating when a comfort class is met. *Annex G –Recommended criteria for acceptable deviations* commends that 3 or 5% are used as a maximum deviation, which on a monthly basis corresponds to 22 or 36 hours or 259 or 432 hours annually. This criterion was chosen in this project as an assessment parameter for whether or not category II is met [DS/EN 15251, 2007].

On a monthly basis deviations of 12 and 25% are used, as recommended in the draft for *'Definition of the indoor environmental quality – Used for Net Zero Energy Buildings (NetZEB)'* produced by the Strategic Research Centre on Zero Energy Buildings.

Assessment of passive house recommendation for excessive temperatures

The passive house institute recommends that temperatures above 25°C occur a maximum of 10% of the time. This recommendation will be controlled for each month as well as on an annual basis.

Assessment of excessive temperatures compared to Danish BR10 requirements for low energy construction

With regard to excessive temperatures, assessments focus on the maximum 100 hours above 26°C and 25 hours above 27°C in critical rooms. This analysis corresponds to the thermal category II requirements, where the comfort temperature goes from 23 to 26°C in summer.

Assessment of problems with insufficient heating

In order to assess whether insufficient heating is a problem, for this project the following requirements have been drawn up, inspired by the BR10 excessive temperature requirements for low energy class 2015 and building class 2020. The 100 and 25 hours are also used, but with temperatures below 20°C and 19°C, respectively. These requirements correspond to winter clothing in category II.

A.2 Atmospheric indoor environment

As indicator of the indoor air quality in the houses, both the houses' CO_2 concentration and relative humidity are measured. However, contributions from e.g. human bio-effluents as well as the process of degassing materials also affect assessments of the air quality in a room. This is not measurable in the same way as the above-mentioned parameters, though, but is instead evaluated via e.g. our sense of smell. Common to all impacts on the atmospheric indoor environment is that the number of dissatisfied residents is reduced when the amount of ventilation is increased, but an increased amount of ventilation also results in increased energy consumption – therefore, it is important to find a balance in this connection. Nevertheless, the building regulations places no direct demands on the atmospheric comfort, but it does demand a minimum amount of ventilation in homes [BR10, 2011].

Criteria for both CO_2 and relative humidity are evaluated and compared to category II from DS/EN 15251. Furthermore, the analysis will determine whether the set point values are violated for more than 24 hours at a time. If this is the case, the requirements for atmospheric comfort are not met. The analysis of whether the different levels have been violated is made on a monthly basis, whereas the demand for category II is analysed on both a monthly and an annual basis.

A.2.2 CO_2

Today, no Danish recommendations for CO_2 levels in homes exist; therefore, the results of this project are evaluated exclusively on the basis of a given level above the outdoor concentration for DS/EN 15251, in which category II must be met.

Assessment of CO_2 with reference to DS/EN 15251

DS/EN 15251 describes four categories of which class II is 500 ppm above the outdoor concentration [DS/EN 15251, 2007]. This assessment criterion is included in the study. All four categories are evident from the table below.

Category	CO_2 concentration above outdoor concentration
I	350
II	500
III	800
IV	>800

Table A.0.2: Recommended CO_2 values from DS/EN 15251.

Exceeding threshold values

The assessment of the CO_2 level also considers the number of periods in which the CO_2 level exceeds category II for 8 consecutive hours. 8 hours was chosen as it should be possible within a relatively short period to regain a low level after a long-term load (e.g. when leaving the bedroom in the morning).

A.2.3 Relative humidity (RH)

As with the CO_2 assessment, DS/EN 15251 is used for the assessment of the relative humidity, in which category II must be met.

Assessment of relative humidity with reference to DS/EN 15251

DS/EN 15251 also introduces four humidity categories. The assessment takes into account whether these categories are met. The categories are shown in the table below.

Category	Relative humidity limits
I	30-50%
II	25-60%
III	20-70%
IV	<20 and >70%

Table A.0.3: Recommended values for relative humidity from DS/EN 15251.

Control of RH < 45%

RH <45% is evaluated, as [SBi196] recommends that this is maintained for a minimum of a month a year, as dust mites die when the relative humidity is below 45%. This analysis looks for a consecutive month where RH < 45%. The acceptable deviation for this period is 10 hours.

Control of RH > 75%

RF > 75% is assessed, as this may cause problems in the constructions. Here RH > 75% is allowed for a maximum of 1% of the time [SBI224].

Exceeding threshold values

The RH assessment also considers the number of periods in which RH exceeds category II for 24 consecutive hours.

A.2.4 Ventilation

In the atmospheric comfort analysis the amount of ventilation will be compared to both CO_2 and relative humidity to determine whether there is a connection between the different steps on which the ventilation system operates and possible deviations from the CO_2 and relative humidity assessment criteria. Analysing graphs with these values, it is considered whether the amount of ventilation is sufficient and whether it is possible to lower the air change from the current 0.5 h^{-1} (= 0.35 l/s per m² heated floor area).

A.3 Daylight

Assessments of the daylight conditions in the houses are based on the building regulations 2008 [BR08] requirements. The following is taken from 'section 6.5.1 In general':

6.5.1(1) Workrooms, occupiable rooms, habitable rooms and shared access routes must have satisfactory lighting without causing unnecessary heat loads.	*(6.5.1(1)) Satisfactory light must be assessed in the context of the activities and tasks intended to be carried out in the room. The requirement for daylight must be viewed in the context of the general health aspects of daylight. The quantity of daylight also affects the energy consumption for electric lighting.*

And under *daylight* in section 6.5.2 one will find the following requirement and instructions:

6.5.2(1) Workrooms, occupiable rooms in institutions, teaching rooms, dining areas, hereinafter called "workooms etc.", and habitable rooms must have sufficient daylight for the rooms to be well lit. Windows must be made, located and, where appropriate, screened such that sunlight through them does not cause overheating in the rooms, and such that nuisance from direct solar heat gain is avoided.	*(6.5.2(1)) In workrooms etc., the daylight can usually be taken to be sufficient if the glazed area of side lights corresponds to a minimum of 10% of the room floor area or, in the case of rooflights, no less than 7% of the room floor area, assuming that the light transmittance of the glazing is no less than 0.75. The 10% and 7% are guidelines assuming a normal location of the building and a normal layout and fitting out of the rooms. If the type of window is not known at the time of design, the frame clear*

	area can be converted to the glazed area by multiplying the clear frame area by a factor of 0.7. The glazed area must be increased in proportion to any reduction in light transmittance (for example solar control glazing) or reduced light ingress to the windows (for example nearby buildings). Daylight may similarly be deemed to be adequate when calculation or measurement can demonstrate that there is a daylight factor of 2% at the workplaces. When determining the daylight factor, account must be taken of actual conditions, including the design of the windows, the light transmittance of the pane and the nature of the room and of the surroundings. See By og Byg (SBi) Guidelines 203, "Beregning af dagslys i bygninger" [Calculation of daylight in buildings] and SBi Guidelines 219, "Dagslys i rum og bygninger" [Daylight in rooms and buildings].

Assessments of the results found in this project will use a daylight factor **of** 2% as a minimum threshold; however, in order for the conditions to be considered good, this should be achieved throughout the room and not only in areas considered workspaces. Thus, the depth of a room is also included in the assessment, as deep rooms should have larger or more high-placed window section than narrow rooms.

A method for determining the daylight factor is described in the report *'Komforthusene - Målinger og analyse af indeklima og energiforbrug i 8 passivhuse 2008-2011'*.

A.4 Acoustic indoor environment

Assessments of measurements of noise from the ventilation system and reverberation times take as their starting point *DS490 Sound classification of dwellings*, as BR08 refers to a functional requirement herein, which is met by complying with class c.

The following extract from BR08 is from chapter *6.4 Indoor climate - acoustics*, section *6.4.2 Domestic and similar buildings used for overnight and accomodation.*

6.4.2(1) Domestic and similar buildings used for overnight accommodation, and ancillary services, must be designed such that those who occupy the buildings are not subjected to noise nuisance	*(6.4.2(1)-(4)) "Domestic buildings" in this context also includes hotels, student halls of residence/dormitories, boarding houses, inns, bedsits, boarding schools, sheltered housing,*

from rooms in adjoining residential and commercial units, from the building services or from nearby roads and railways.	*residential childcare institutions and similar buildings used for overnight accommodation.* *"Common space" means, for example, occupiable space shared by several domestic buildings; and stairwells or corridors.* *The functional requirement for domestic buildings is deemed to be met if they are built as class C in DS 490, Sound classification of dwellings.*

The tender documents for the Comfort Houses presented the following acoustics requirements for the houses:

Acoustic requirements
For the building the acoucstic capacibility should be taken in to consideration, so the house appear as a comfortable house to live in. Specific the internal acoustic problematics should be taken in to consideration, fx. reverberation time. For all construction joints, installations and lead-in the acoustic capacibility should be ensured. [Our translation]

Considering the DS490 definitions of class b and class c, respectively, the following definitions are found [DS490]:

Acoustic category B
Category with significant better acoustic conditions than the minimum requirement from the building regulation for housing. The occupants are only limited affected from sound. [Our translation]

Acoustic category C
Category corresponding to the intentions as the minimum requirement form the building regulation. Between 15% and 20% of the occupants are anticipated to be affected form sound. [Our translation]

Comparing the requirements in the tender documents and the definitions of class b and class c, the measurement project establishes a requirement for meeting level b.

The method for measuring noise and reverberation times is described in the report *'Komforthusene - Målinger og analyse af indeklima og energiforbrug i 8 passivhuse 2008-2011'*.

A.4.1 Requirements for noise from building services

Assessing the noise from building services, which in all Comfort Houses includes noise from ventilation systems/compact units, compressors, pumps etc., the following applies [DS490]:

The limiting values for sound from the building services are applied for each installation and are applied for an unfurnished room with closed windows and doors. If the measurements are done for other room conditions corrections in agreement with [1] in bibliography need to be made. [Our translation]

For cases with low frequent sound the A- weighted sound pressure level in the low frequent range, $L_{p,A,LF}$, should not exceed 25 dB during the day (7am-6pm) or 20 dB during the evening and night (6pm-7am). For acoustic category A and B the limiting values should be ensured, which is 5 dB lower. The limiting values for low frequent sound are related to a special measurement method, see [4] in bibliography. [Our translation]

Table A.0.4 outlines the requirements for the maximum threshold values for noise from building services.

Room type		Category A [dB]	Category B [dB]	Category C [dB]	Category C [dB]
In dwellings, kitchens and common rooms	$L_{Aeq,T}$	20	25	30	35

Table A.0.4. Noise from building services. Threshold values given as highest values for A-weighed equivalent sound pressure level [DS490].

A.4.2 Reverberation time requirements

The DS 490 reverberation time requirements are outlined in Table A.0.5. Assessments of the results use the 'shared living room' requirements.

Room type	Category A *T* [s]	Category B *T* [s]	Category C *T* [s]	Category C *T* [s]
In stairways and corridors with access to more than 2 residences or business units, at 500 Hz, 1000 Hz and 2000 Hz.	1.0	1.0	1.3	1.3
In corridors in care homes etc. where the corridors in some extend are used for staying, at 500 Hz, 1000 Hz and 2000 Hz.	0.9	0.9	0.9	0.9
Common rooms, at 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz.	0.6	0.6	0.6	No demands
NOTE- the maximum level at 125 Hz is 0.9 s in common rooms.				

Table A.0.5. Reverberation time requirements. Threshold values given as highest values for each set of octave band [DS490].

A.5 Overview of assessment criteria

The table below provides a complete overview of the indoor environment parameters assessed in the Comfort Houses.

		Maximum deviation	
	Criterion	Month	Year
Thermal indoor environment			
General assessment	Category II	12 and 25%	3 and 5%
Excessive temperature	25°C	10%	10%
	26°C	100 h	100 h
	27°C	25 h	25 h
Cooling temperature	20°C	100 h	100 h
	19°C	25 h	25 h
Atmospheric indoor environment			
CO_2	Category II	12 and 25%	3 and 5%
	Category II	8 h consecutive	-
Relative humidity	Category II	12 and 25%	3 and 5%
	Category II	24 h consecutive	-
	70%<φ<30%	24 h consecutive	-
	φ<45%	1 month consecutive except 10 hours	-
	φ>75%	1%	-
Daylight factor	2% at the back wall	-	-
Acoustics			-
Reverberation time	Class B	-	-
Building services	Class B	-	-

Table A.0.6: Overview of indoor environment assessment criteria.

A.6 Energy consumption

In order to evaluat the houses' energy consumption a report is produced containing data of the energy used for space heating, heating for domestic hot water as well as the total electricity consumption, thus outlining the various consumptions.

As the measuring equipment in the houses is also powered by electricity this will be deducted from the total electricity consumption. The report *'Komforthusene - Målinger og analyse af indeklima og energiforbrug i 8 passivhuse 2008-2011'* presents an overview of the measured consumption.

A.7 Meeting the passive house criteria

In order to control whether the houses meet the passive house criteria the necessary data of the energy consumption for space heating and the primary energy consumption, i.e. the total electricity consumption, will be included in a separate monthly and annual data report. This will control whether the measurements conducted in the houses reveal an agreement between the calculated PHPP values. The passive house criteria are evident from Table A.0.7.

Space heating demand	15 kWh/m² pr year
Primary energy demand	120 kWh/m² pr year
Airtightness	0,6 h^{-1} v. ΔP = 50 Pa

Table A.0.7. The passive house criteria [PHPP2007].

Using the report following the blower door tests, it will be controlled whether airtightness is achieved.

A.8 Meeting the passive house recommendations

In addition to control of the passive house criteria, which must be met for a house to be a certified passive house, whether the project meets the passive house recommendations is also examined. In this connection a report is produced containing the measured data, comparing it to the outlined recommendations. The recommendations are evident from Table A.0.8.

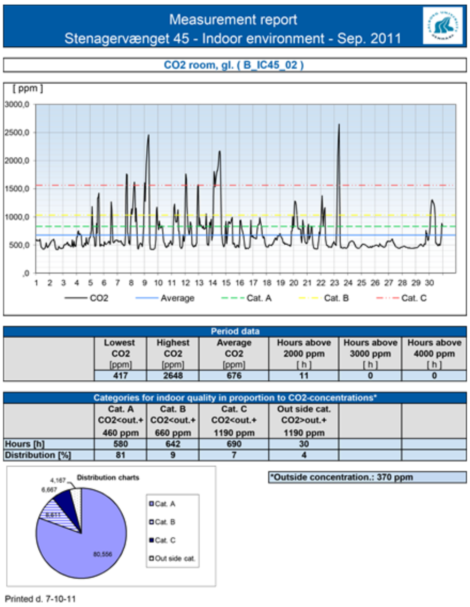
Heating load	max 10 W/m²
Excessive temperatures	max. 10% (t<25°C)
Window U-value	max. 0,80 W/m²K

Table A.0.8. The passive house recommendations [PHPP2007].

The number of excessive temperature hours is counted on a monthly basis and will be calculated on a monthly as well as an annual basis. According to PHPP, excessive temperature hours must be counted when the temperature exceeds 25°C. Finally, the U values of the windows will be controlled in the PHPP calculation for each house.

Appendix B – Measurements from the houses

This appendix outlines the completed measurements and the measuring instruments used. Measurement points and their position are noted in the house-specific reports.


Measurement report
Stenagervænget 45 - Indoor environment - Sep. 2011

CO2 room, gl. (B_IC45_02)

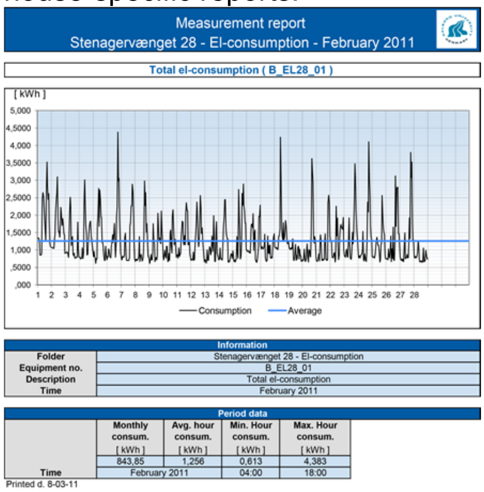
Period data						
	Lowest CO2 [ppm]	Highest CO2 [ppm]	Average CO2 [ppm]	Hours above 2000 ppm [h]	Hours above 3000 ppm [h]	Hours above 4000 ppm [h]
	417	2648	676	11	0	0

Categories for indoor quality in proportion to CO2-concentrations*						
	Cat. A CO2<out.+ 460 ppm	Cat. B CO2<out.+ 660 ppm	Cat. C CO2<out.+ 1190 ppm	Out side cat. CO2>out.+ 1190 ppm		
Hours [h]	580	642	690	30		
Distribution [%]	81	9	7	4		

*Outside concentration.: 370 ppm

Printed d. 7-10-11

Figure B.0.2: *Example of CO_2 report.*


Measurement report
Stenagervænget 28 - El-consumption - February 2011

Total el-consumption (B_EL28_01)

Information	
Folder	Stenagervænget 28 - El-consumption
Equipment no.	B_EL28_01
Description	Total el-consumption
Time	February 2011

Period data				
	Monthly consum. [kWh]	Avg. hour consum. [kWh]	Min. Hour consum. [kWh]	Max. Hour consum. [kWh]
	843,85	1,256	0,613	4,383
Time	February 2011		04:00	18:00

Printed d. 8-03-11

Figure B.0.1: *Example of report concerning the total electricity consumption.*

All measurements are compiled in the energy management programme Omega EMS, via which monthly reports have been produced for all measurements. Examples of these reports are evident from Figure B.0.1 and Figure B.0.2.

B.1 Indoor environment

For all the houses, the temperature (T), relative humidity (RH) and CO_2 level (CO_2) are measured throughout the project period. For these measurements GC-10 and GD-47EE *Eltek transmitters* are used; the former measures T/RH and the latter T/RH/CO_2. GD-47EE transmitter need 220V, while the GC-10 is powered by four AA batteries.

Figure B.0.3: Eltek equipment used for measuring the indoor environment.

The transmitters forwards data to a RX-250-AL data logger placed in Stenagervænget 39. If necessary, the signal from the other seven houses is intensified with the help of a repeater placed in the technical room. The equipment's precision interval from -10°C to 50°C is evident from the following table. Figure B.0.3 presents the equipment. The larger transmitter is a GD-47EE and the small one is a GC-10; the logger is placed to the far right.

Sensor	Measuring interval	Precision
CO_2	0 – 5000 ppm	50 ppm + 3% of the measured value
Realitve humidity	0 – 100%	10 – 90% RH ± 2%
		0 – 100% RH ± 4%
Temperature	-20^{o}C – 65^{o}C	-5^{o}C – 40^{o}C ± 0,4^{o}C
		-20^{o}C – 65^{o}C ± 1,0^{o}C

Table B.0.1: Uncertainty of Eltek equipment.

B.2 Energy for space heating and domestic hot water

Figure B.0.4: *HGQ1 heat consumption measurer.*

As with the indoor environment the energy used for space heating and domestic hot water is measured throughout the project period. This is done using HGQ1 measuring equipment provided by Brunata A/S (see Figure B.0.4), type-approved for determining district heating and thermal energy levels in other water-based heating systems.

Table B.0.2 outlines the uncertainty of the HGQ1 measurer. The numbers given in ( ) apply to measurers with qs < 3m3/h and flow < 10% of qs. For more information, see Brunata information material. The measurements are peak measurements, integrating during a varying time span, until a value of 1 kWh is reached.

Temperature difference	Energy
Δθ < 10 K	± 6% (± 8%)
10 K ≤ Δθ < 20 K	± 5% (± 7%)
20 K ≤ Δθ	± 4% (± 6%)

Table B.0.2: Uncertainty in HGQ1 measurer for domestic hotc water and space heating.

B.3 Electricity consumption

In addition to the two above-mentioned measurements, the electricity consumption is measured. For all houses the overall electricity consumption is measured. Furthermore, for each house the parameters that should be registered are defined. These measuring points can be found in the house-specific reports. The primary and secondary meters are integrated into the same panel and are evident from Figure B.0.5.

Figure B.0.5: *Electricity meter.*

B.4 Electricity consumption from measuring equipment

The electricity consumption of each house is assessed. The table below presents the electricity consumption of the different equipment installed in the houses. The Eltek data logger was only installed in Stenagervænget 39. Data from all houses is compiled here.

Equipment description	**Effect [W]**
Eltek humidity measures with external power supply, GS-44	0,7
CO_2Eltek temp, humidity, CO_2-measures, GD-47	1,3
Brunata (without use of display)	3,7
Brunata (Utilises display)	3,8
Eltek datalogger (RX-250-AL2M) logging	11,5
Eltek datalogger (RX-250-AL2M) idle	10,8
3com router	8,5
BTR-datalogger	6,0

Table B.0.3: Electricity consumption of measuring equipment.

Appendix C: Calculating the daylight factor

Calculating the daylight factor in a number of selected rooms, primarily the lighting level in living rooms and kitchens-dining areas is measured. The method of measurement follows the directions provided in *SBI-anvisning 219, Dagslys i rum og bygninger* [SBi219].

C.1 Definition of daylight factor

The daylight factor (DF) is calculated as the relation between the lighting level [lux] at a point inside the room (E_{indoor}) and the lighting level in the open ($E_{outdoor}$) at a horizontal level with a free horizon and evenly cloudy sky.

$$DF = \frac{E_{indoor}}{E_{outdoor}}$$

The daylight factor is given in %.

C.2 Determining the daylight factor

In order to determine the daylight factor simultaneous measurements were made of the lighting level indoors and outdoors on a day with an evenly cloudy sky. The indoor measurements were made 0.85 m above the floor along a 90 degree angle from the window towards the back wall/opposite wall in the room. In some cases, measurements were made between two walls, if the space between these was central to the room.

Figure C.1. Measuring the daylight in the Comfort Houses.

Appendix D: Measuring reverberation times and noise from ventilation systems

The measurements of reverberation times and noise from ventilation systems are conducted as described in [DS490] and [Hyldgård]. All measurements are made in empty houses, the doors to adjacent room closed. This is the correct way to measure noise from building services. Reverberation times are similarly measured in empty rooms and depend on the surfaces of the room in question. Normally, this types of measurement should be made in a furnished room [SBI217], which may result in a reduced reverberation time, as furniture often have a noise-reducing effect.

D.1 Determining reverberation times

Reverberation is defined as the time it takes the sound pressure level to drop 60 dB. The reverberation time for a room depends on the frequency of the sound and is therefore measured for each set of octave bands. To measure reverberation times, a sound pressure meter is installed in the room in question. In addition, a sound source that can quickly be turned off is used. The sound source emits octavo-filtered noise. The equipment used in the measurements is evident from Figure D.1.

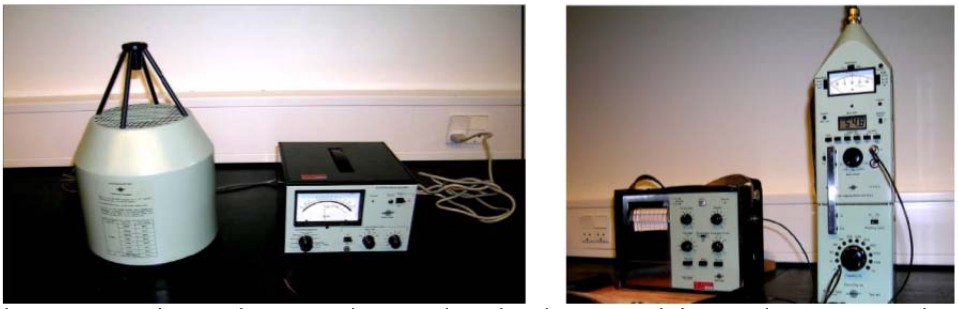


Figure D.1. Equipment for measuring reverberation time. From left: sound source, sound generator, recorder and sound pressure meter [Hyldgård].

The reverberation time is, as mentioned, measured for each set of octave bands (125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz and 8000 Hz). Following each measurement, the recorder produces a print as shown in Figure D.2. The reverberation time for each set of octave band is determined on the basis hereof.

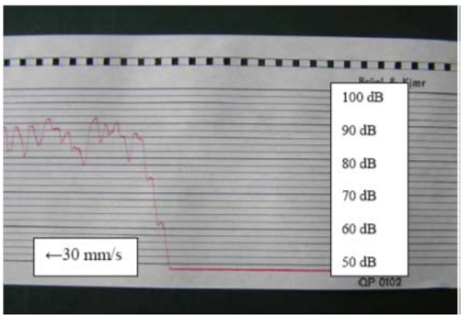


Figure D.2. Examples of print from reverberation time measurement [Hyldgård].

Figure D.3. Measurement of reverberation time in the Comfort Houses.

D.2 Measurement of noise from the ventilation system

Measurements of noise from the ventilation system are made in the living room and kitchen-dining area. The sound pressure level is measured for sets of octave bands between 31.5 Hz and 8000 Hz. The readings are recorded in an NR diagram, so as to produce an NR curve.

However, assessment of the results only considers the readings measured in dB, as this is the indication used in DS490. Figure D.4 gives an example of an NR diagram.

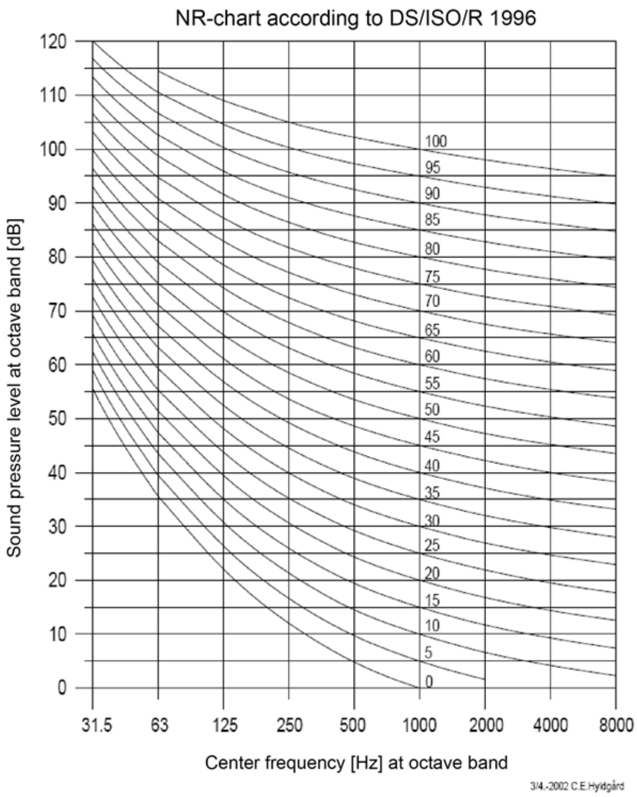


Figure D.4. NR diagram [Hyldgård].

Appendix E: Comparison of weather data (DRY & Skibet)

The external temperature measured in the weather station in Skibet is shown on the figures below alongside the DRY (Design Reference Year). The comparison is made to illustrate the difference between a standard weather data set and actual measurements.

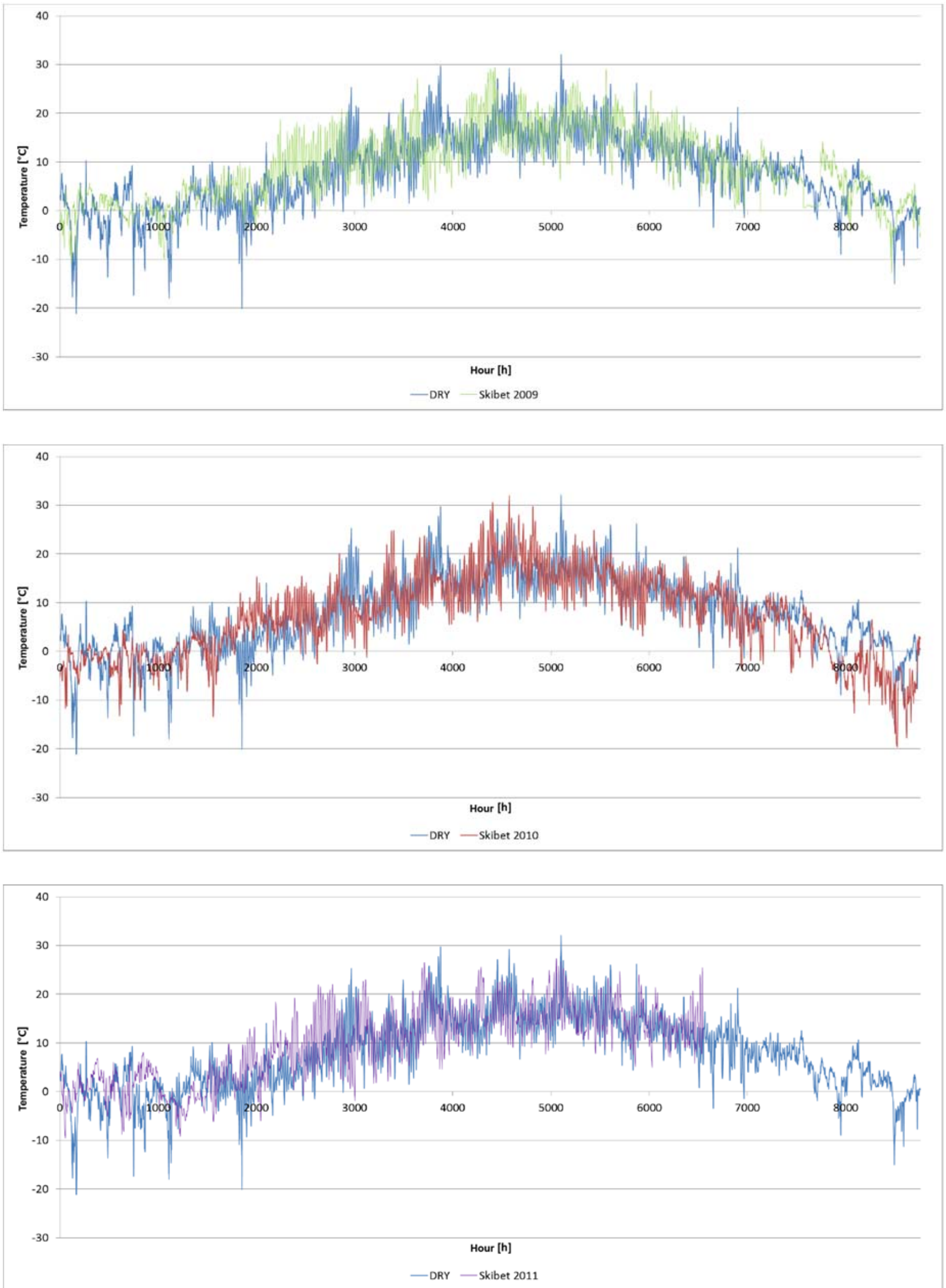


Figure E.1: Comparison between DRY and weather data from Skibet in 2009, 2010 and 2011, respectively.

Overall, the measured weather data corresponds to the DRY temperature; however, different periods do show deviations from one year to the next.

The figure below presents a part of July from all three years and July in DRY. This month was chosen as an example, as many houses experience excessive temperature problems in July 2010.

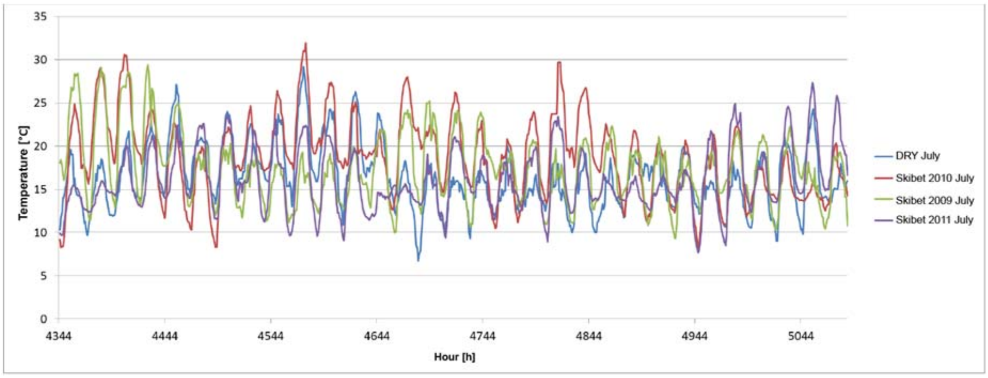


Figure E.2: Comparison of the DRY and weather data from Skibet in July.

It is evident that the DRY temperature is below the measured values for a part of the month. At more than one time July 2010 has the highest measured values, which is a part of the explanation for the high indoor temperatures in the houses. The average temperature from July 2010 was 18.8°C, which is significantly higher than the other two years: 17.4°C in 2009 and 16.1°C in 2011. In DRY the average temperature for July is 16.4°C.

Appendix F: Comparison of weather data (DMI-Billund & Skibet)

The measured external temperature at the weather station in Billund is shown on Figure F.1 alongside the measured weather data from Skibet. The comparison is made to illustrate the difference between a DMI weather data set and actual measurements, as the DMI measurements from Billund are used to generate weather data in Meteonorm.

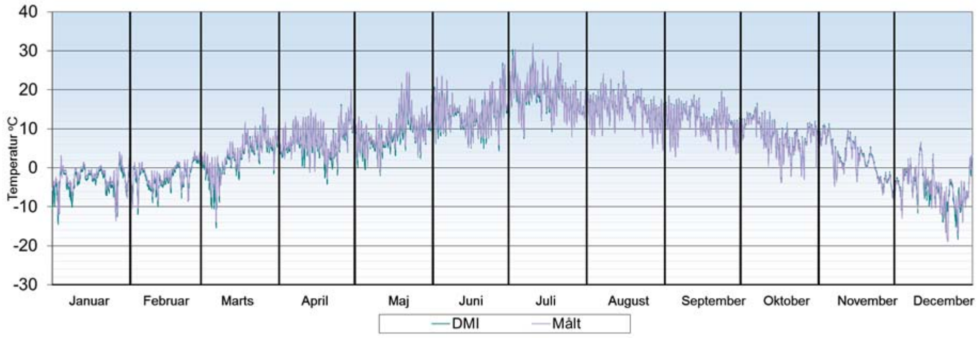


Figure F.1: Comparison of weather data measured in Skibet and Billund in 2010.

Table F.1 shows the difference, in monthly average values, for the two measuring stations. It is evident from the table that the difference is minimal, and the entire year is close to the measuring uncertainty of the temperature sensor in Skibet, cf. Appendix B: 'Measurements from the houses'.

	Skibet	**DMI-Billund**	**Difference**
January	-2,4	-3,5	1,1
February	-1,7	-2,4	0,8
March	3,5	2,7	0,7
April	7,5	6,9	0,6
May	9,6	8,9	0,7
June	14,3	13,8	0,5
July	18,6	18,3	0,3
August	15,0	15,3	-0,2
September	11,7	12,0	-0,3
October	7,8	8,1	-0,3
November	1,9	2,3	-0,3
December	-5,1	-5,3	0,2

Table F.1: Comparison of average temperature for 2010 measured in Skibet and in Billund.

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