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Satisfaction with indoor climate in new Danish low-energy houses

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SUMMARY

This paper focuses on the perceived indoor climate in new Danish low-energy houses and discusses the issue of overheating in relation to evaluation methods and user satisfaction. The user satisfaction was evaluated among 370 owners of new low-energy class 2015 detached single-family houses based on a questionnaire survey. The survey evaluated overall satisfaction, and more specifically satisfaction with the indoor climate parameters temperature, draught, air quality, noise and daylight, as well as technical installations of the house. The survey showed satisfaction with living in new low-energy houses and more than 90% perceived the indoor environment as satisfactory both in summer and winter. The majority perceived the various indoor climate parameters to be better in their new low-energy house compared with conditions in their former house. Compared with earlier studies on previous generations of low-energy houses, problems with overheating seemed to have decreased, as only 12% found temperature conditions to be unsatisfactory in summer.

KEYWORDS

Indoor climate, Low-energy house, Occupant satisfaction, Overheating, Questionnaire survey

INTRODUCTION

The Danish Building Regulations 2010 (BR10, 2010) defines minimum requirements for the energy performance of buildings. In order to encourage the development of more energy-efficient buildings, BR10 also includes the supplementary and more ambitious voluntary low-energy class 2015 and building class 2020. The requirements for the voluntary classes are expected to form the basis for the revising of the Danish Building Regulations in 2015 and 2020.

According to the current BR10, the yearly energy demand for heating, ventilation, cooling and hot water for a residential low-energy class 2015 house, should be less than $(30 + 1000 / A_e)$ kWh/m², where A_e is the heated floor area. For building class 2020 the energy demand is further reduced and must not exceed 20 kWh/m². In 2012 and 2013, the proportion of low-energy class 2015 buildings was approximately one third of all newly constructed buildings in Denmark. In 2013, the use of building class 2020 was still very limited and therefore the survey in this paper refers primarily to low-energy class 2015.

Before the supplementary requirements for low-energy class 2015 become standard for all new buildings in Denmark, an evaluation was called for to evaluate the experience gained among 1) house owners to identify possible negative consequences of living in detached low-energy single-family houses and 2) construction professionals to identify unforeseen consequences when designing and building to the class 2015 standard (Knudsen and Kragh, 2014). Experience will show the strengths of the low-energy class, but also identify areas where changes are desirable, before low-energy class 2015 becomes the minimum requirement in the next Danish Building Regulations 2015.

Earlier studies have shown that previous generations of low-energy houses had some problems with the indoor climate and especially too high room temperatures in summer, so-called overheating, and opposite too low temperatures in winter and also noise from technical installations (Larsen, 2011, Knudsen et al., 2012 and 2013). Moreover, these earlier studies also show a need for more robust and easy-to-use technical installations that are fully operational at the time of moving into the house.

The undesired overheating in low-energy houses was addressed in the latest revision of BR10 by only allowing the air temperature to be above 26 °C for 100 hours and above 27 °C for 25 hours during a specified reference year. These limits are based on the guidelines for tolerance exceedance on warm days in Danish Standard, DS 474E Code for Thermal Indoor Climate (1995).

The limits are in line with the 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" (2007) which prescribes the limit for thermal comfort to be 26 °C in summer in residential buildings to comply with category II with an allowed exceedance in 3% of the time from May to October, which corresponds to approximately 131 hours.

Design criteria for the thermal environment is based on the thermal comfort indices PMV-PPD (predicted mean vote - predicted percentage of dissatisfied) which link together air temperature, radiation, air velocity and humidity, levels of activity and thermal insulation of clothing. The thermal comfort indices PMV-PPD were developed by Fanger (1970) on the basis of laboratory studies with human subjects assessing the thermal environment under controlled conditions in climate chambers. Therefore, the PMV-PPD indices may be suitable for application in controlled office environments but perhaps less suitable for homes where residents may have other individual preferences for temperature conditions, and the assessment of temperature may depend on other criteria than in an office environment. For example they may make a trade-off in relation to economy and energy consumption, which can lead to a decision that allows some rooms to be cold during winter.

The objective of this study was to evaluate the satisfaction among owners of the new generation of low-energy class 2015 detached single-family houses. In this paper, the satisfaction with the perceived indoor climate is analysed, with particular focus on temperature conditions in summer and whether the low-energy class 2015 tolerance exceedance of temperature on warm days are working in practice.

METHODS

The evaluation among owners of new detached low-energy houses was conducted as a questionnaire survey. It included i.a. questions on their overall satisfaction with living in a new low-energy house, and in particular their satisfaction with the indoor climate (temperature, draught, air quality, noise and daylight) and experience with the use of technical installations.

It was desirable to investigate whether the house owners perceived the indoor climate in the new low-energy houses to be better or worse than in their former dwellings. More than 54% came from dwellings built before 1980. As it was not feasible to ask the house owners before they moved into their new house, they were asked to compare the perceived indoor climate in their new house with the indoor climate in their former dwelling.

The survey was conducted in October 2013. It was carried out by sending a letter with a brief description of the project and an invitation to participate in the survey by filling in a questionnaire, using an online survey system (SurveyXact). It was assumed that all involved households had access to a computer and the internet, since 93% of households in Denmark have this access. House owners were promised anonymity. To encourage the house owners to fill in the questionnaire, they were offered to participate in the draw for a gift, value about 100 euro, for every 100 replies. By deadline, 370 house owners of a total of 869 had answered, corresponding to a response rate of 43%. This relatively high response rate might be due to the occupants' involvement and interest in new low-energy housing. It should be mentioned that no reminders were sent out.

The questionnaire included 40 questions about: The house, overall satisfaction, former house, family, perceived indoor climate (temperature, draught, air quality, noise and daylight), windows and airing habits in winter, use of technical installations, heat consumption and a series of supplementary open questions to allow for individual comments.

Identifying houses to be studied

Since 1997, Danish law has stipulated that all property for sale should be inspected by a trained energy consultant. The inspection is mandatory for both new and existing buildings. The energy consultant should prepare an energy certificate with an energy rating on a scale from A to G. The certificate is registered by the consultant and compiled in the Energy Performance Certificate Scheme database (EPC, 2013). From this database 869 low-energy single-family houses constructed in 2010 (1%), 2011 (7%), 2012 (55%) and 2013 (37%) were identified.

The houses

The houses were built by approximately 130 different companies. The average floor area of the houses was 186 m². The houses were mainly (94%) heated by floor heating and they were equipped with a wide range of technical installations as shown in Figure 1. It was not asked directly whether the houses had some kind of solar shading, but 41% of the house owners expressed that they had the option to regulate solar shading and nearly all (40%) used this option.

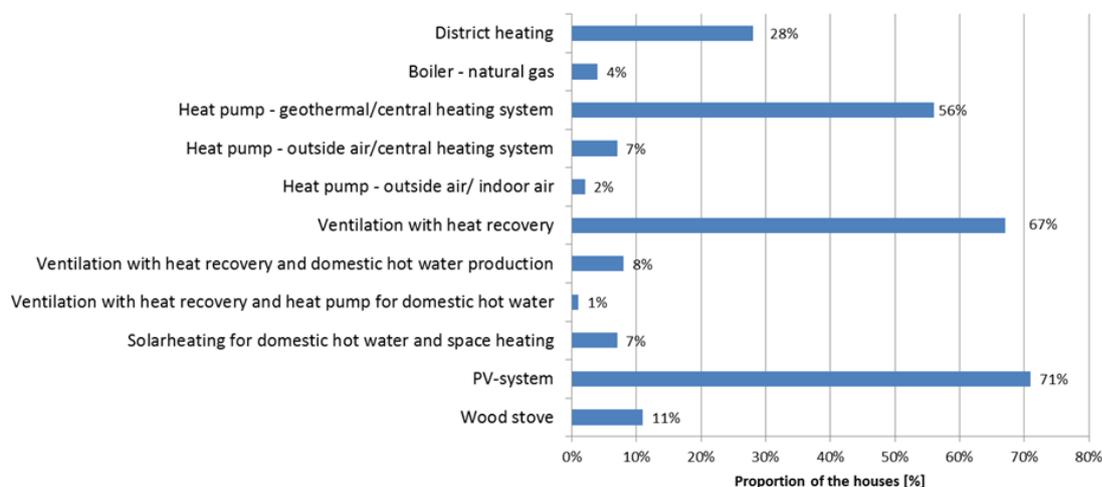


Figure 1. Technical installations as reported by the house owners of 370 detached low-energy single-family houses.

RESULTS

House owners' overall satisfaction

Overall, the house owners rated it to have been a positive experience to move into and live in their new low-energy houses, since 93% of the house owners would recommend others to live in a low-energy house. The important reasons formulated by the house owners themselves as comments were good indoor climate and low energy and operating costs.

Perceived indoor climate

After defining the perceived indoor climate by the five parameters temperature, draught, air quality, noise and daylight, the house owners were asked to make an overall assessment of the indoor climate. More than 90% of the house owners found that the indoor climate was generally satisfactory in summer (93%) and in winter (94%) with only 4% and 2% expressing dissatisfaction in summer and winter.

In the following the house owners' assessments of the five specific indoor climate parameters are presented.

The temperature conditions were experienced as satisfactory by 84% in winter, and 73% experienced satisfactory temperature conditions in summer, see Figure 2. The temperature was found to be unsatisfactory by 4% in winter, compared with 12% in summer. During winter, 82% never experienced that it was too cold, see Figure 3. It was indicated by 1% and 5% that it was too cold, daily and weekly, respectively. As in previous studies of low-energy houses, the main reason for dissatisfaction with temperature conditions was that it was too hot in summer. This was the case for as many as 19% and 32%, daily and weekly, respectively, see Figure 4. Large windows facing south were mentioned as the reason for the high summer temperatures. Some house owners commented that they had also experienced periods when it was hot in summer in their former house. Some house owners mentioned that a longer response time of their floor heating system made it difficult to regulate the temperature. It was emphasised that there was a more constant temperature in the new house. In comparison, only 1% and 5% found that it was too cold in winter daily and weekly, respectively, see Figure 3.

In winter, 94% of the house owners never experienced draught problems and similarly 96% in summer. Only 3% of the house owners found draught conditions unsatisfactory in winter and 2% in summer and in this case the main problems were due to the opening of windows and being near the inlet of the ventilation system.

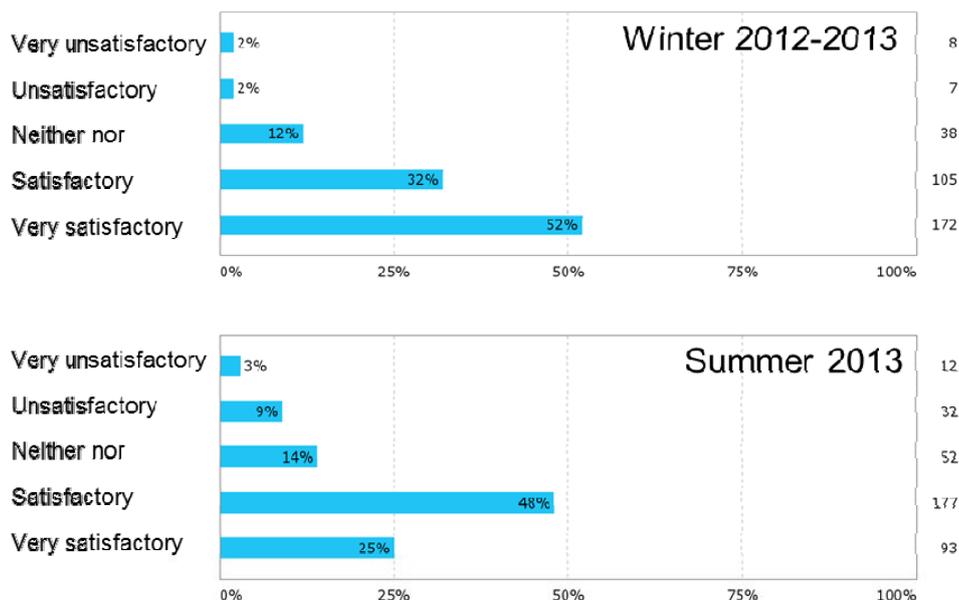


Figure 2. Answers to the question "How did you perceive the temperature conditions in your house, winter 2012-2013 and summer 2013?"

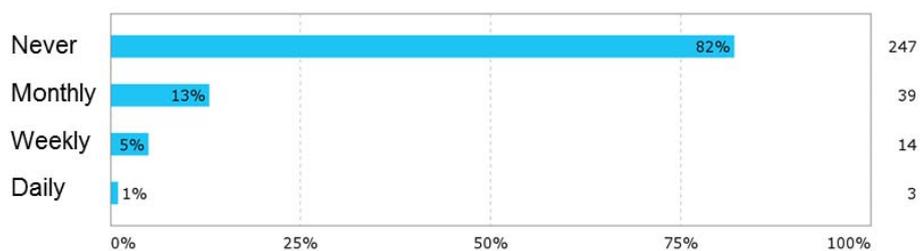


Figure 3. Answers to the question "How often have you experienced that it was too cold during the winter 2012-2013?"

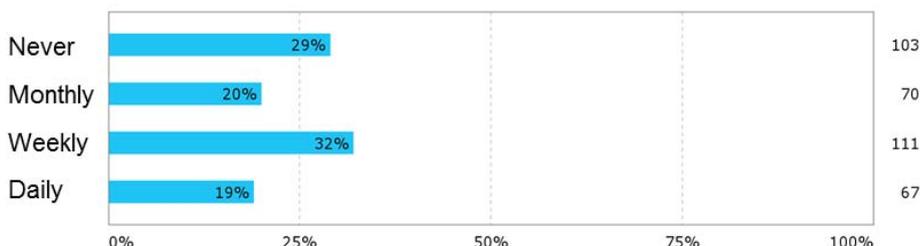


Figure 4. Answers to the question "How often have you experienced that it was too hot during the summer 2013?"

The air quality was perceived as satisfactory by 88% in winter, and by 90% in summer. Only 4% found the air quality unsatisfactory in winter against 3% in summer. To a modest extent, it gave rise to dissatisfaction with the air quality that the air felt dry in winter. Problems with dry air were reported by 7% to be daily and 11% to be weekly. Some house owners emphasised dry air and odours from a neighbour's wood stove in connection with the question of air quality.

Noise conditions were perceived as satisfactory by 84% in winter, and 86% perceived the noise conditions as satisfactory in summer. The noise conditions were found by 6% to be unsatisfactory in winter compared with 4% in summer. To a minor extent, the ventilation system gave rise to dissatisfaction with noise conditions. Problems with noise from the ventilation system were reported by 9% to be daily and 6% to be weekly in winter against 12% and 7% respectively in summer. Other technical installations than the ventilation system caused problems with noise daily for 6% and weekly for 4% in winter and 6% and 3% respectively in summer. The house owners' comments included the ventilation system and heat pump as sources of noise, but in most cases it was not a big problem, but something you could live with in light of the perceived advantages of the house. It was stated by 57% that there was no nuisance from noise in any room. As expected, annoying noise was found to come

from the utility room, which was reported by 18%. Notably the results also showed that 13% perceived annoying noise in the bedroom.

Daylight conditions were experienced to be satisfactory in winter by 91%, and by 94% in summer. Daylight conditions were found to be unsatisfactory by 2% in both winter and summer. To a modest extent, glare in summer gave rise to dissatisfaction with daylight conditions. It was indicated by 4% and 11% that this was the case on a daily and weekly basis, respectively. A few house owners perceived that there was too much daylight, 3% on a daily basis and 8% on a weekly basis. In their comments, the house owners suggested possible building solutions, including roof overhangs and exterior solar shading; some explained that they had retrofitted their house with marquees, curtains and blinds to overcome problems.

Perceived indoor climate in the new low-energy house vs. the former dwelling

A majority of house owners perceived the various indoor climate parameters temperature, draught, air quality, noise and daylight to be better (84%, 85%, 84%, 67% and 77% respectively) in their new low-energy house compared with the conditions in their former dwelling, see Figure 5. Only a minority of house owners perceived the individual indoor climate factors, temperature, draught, air quality, noise and daylight to have become worse (4%, 2%, 2%, 8% and 2% respectively) in their new low-energy house.

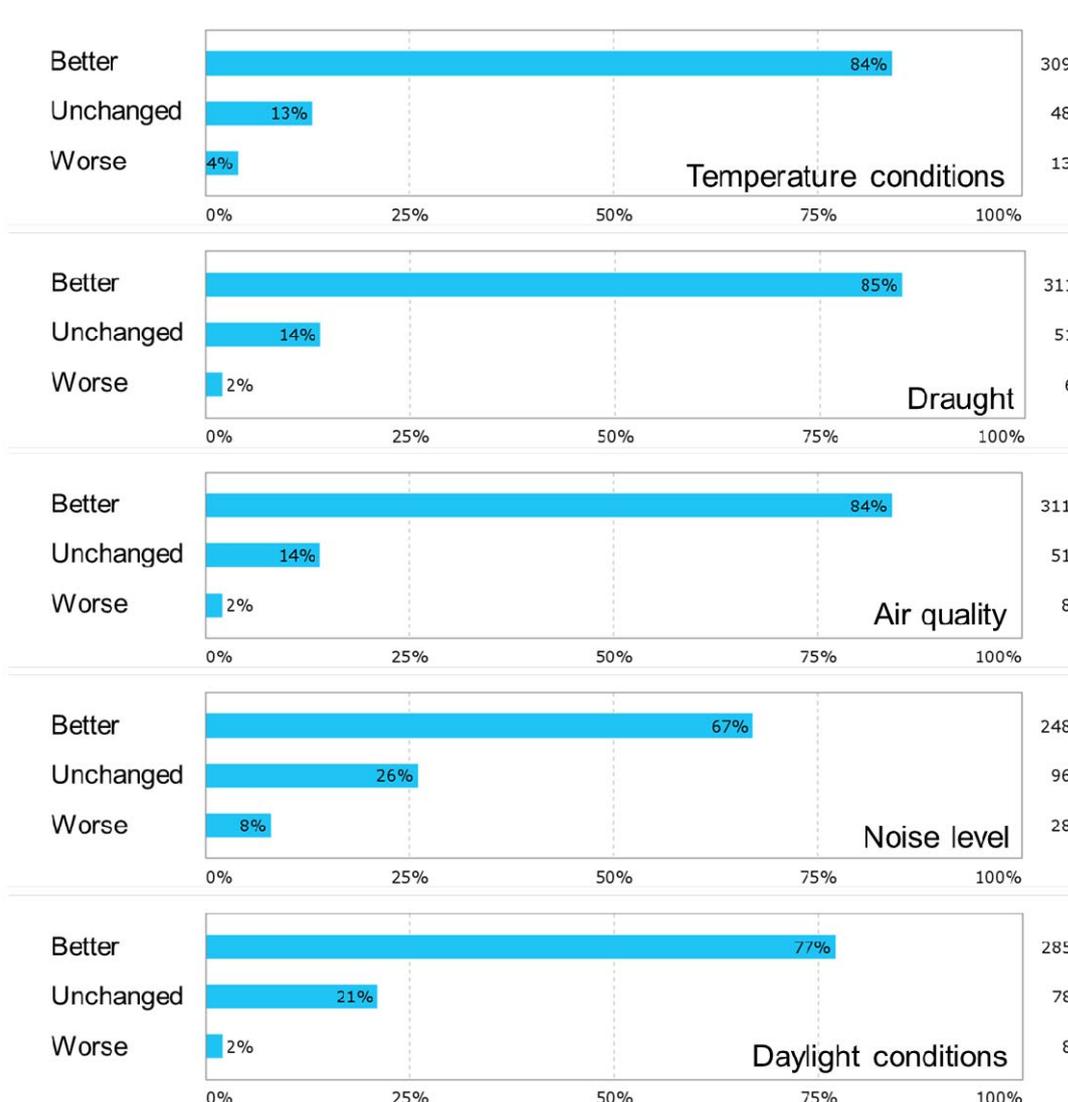


Figure 5. Answers to the question “How do you perceive the temperature conditions, draught, air quality, noise level and daylight conditions in your new house compared with your previous dwelling?”

About half of the house owners indicated that the temperature in their new house was higher in summer (52%) and winter (48%) compared with their former house, while 19% indicated that the temperature had been lower in summer, and 6% indicated that the temperature had been lower in winter, see Figure 6. Large windows were mentioned as the reason for the high summer temperatures. The fact that nearly half of the house owners expressed that the temperature in their new house was higher than in their former dwelling, might indicate that some of the potential energy saving has been transformed into better thermal comfort.

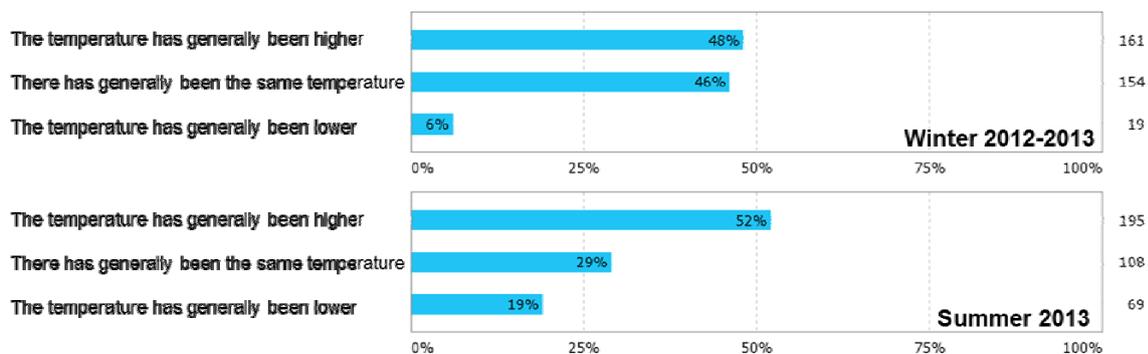


Figure 6. Answers to the question “How was the temperature indoors in your new house in the winter 2012-2013/summer 2013 compared with your previous dwelling?”

Technical installations

House owners were asked whether they had received sufficient information on how the house's various technical installations worked. Nearly two thirds found that they had enough information, while about one third (38%) did not find that they had received sufficient information. Among the latter group of house owners, 83% lacked information on the ventilation system, 49% lacked information on the heating system, 47% lacked information on the heat pump and 31% lacked information on solar cell systems for electricity generation.

House owners were also asked whether they had experienced small or big problems with the technical installations. Big problems had been experienced by 9% in winter and 6% had experienced big problems in summer. Small problems were experienced by 31% in winter and by 24% in summer. The house owners' comments elaborated the problems and the recurrent problems were focused on commissioning problems with the heating system, heat pump and ventilation system immediately upon moving into their new house.

Regulation and user interaction

House owners were asked about their habits of opening windows slightly or completely in winter. About two thirds of the house owners opened windows during the day, and one third had open windows during the night. Half of the house owners opened windows only for a short time during the day. The reasons given for opening windows was a wish for air out, fresh air and for cooling. The wish for a cool bedroom and airing of the bathroom was mentioned by several.

House owners were also asked whether they had found that they were able to regulate, and whether they had used the option to regulate the room temperature, the ventilation and the solar shading. It was found by 97% that they had the option to regulate the room temperature, and 78% were using the option to regulate the temperature. It was experienced by 90% that they had the option to regulate ventilation, and 55% used the option to regulate the ventilation. It was experienced by 41% that they had the option to regulate solar shading and nearly all (40%) used the option of adjusting the solar shading. Several house owners noted that solar shading was needed; several had established internal shading in the form of curtains and blinds.

DISCUSSION

Overall, the house owners evaluated it to be a positive experience to move into and live in their new low-energy houses and they would recommend others to live in a low-energy house. They explained it by their experience of good indoor climate and low energy consumption and consequently low operational costs. A majority was more satisfied with the indoor climate in their new house compared with their former dwelling.

Earlier studies have found that prerequisites for ensuring that occupants are satisfied with the indoor climate in low-energy houses, among other things, are a strong focus on preventing uncomfortably high temperatures during summer and uncomfortable noise from technical installations (Larsen, 2011, Knudsen et al., 2012). Solutions are available, e.g. by combining external solar shading, appropriate window design and orientation and facilitating effective use of natural and mechanical ventilation and noise reduction at ventilation inlets.

In a previous study the indoor environment was evaluated in three of the first certified passive houses in Denmark, the so called Comfort Houses (Brunsgaard et al., 2012). They evaluated the indoor environment using both quantitative measurements and qualitative interviews. The thermal comfort was evaluated using the guidelines set out in the European criteria for the indoor environment, DS/EN/CR 1752, which were developed for office buildings. However, the criteria were used to evaluate the indoor environment in dwellings. Generally a problem with too high temperatures in summer was identified based on the temperature measurements and confirmed by interviews with the occupants. The high temperatures were caused by a combination of unsuitable design and inappropriate user behaviour. The authors point out that the lessons learned from these pilot projects should ensure that specific requirements to the indoor climate are part of the design criteria. Furthermore, the occupants should be trained to understand how their behaviour can support the regulation of the house. They also point out the fact that comfort levels in houses are often a result of the desires and resulting choices of the occupants, e.g. one person would like a temperature of 20°C in the living room whereas others would prefer 23°C. This corresponds well with the fact that BR10 does have specific requirements to the thermal comfort during summer for new low-energy houses. However, the study also suggests that the comfort levels in dwellings may be influenced by personal preferences, which supports that the situation in dwellings is less rigid than that of offices.

The recommended design values for the indoor temperature for the summer season in DS/EN 15251 are identical for dwellings and offices even though the building typology and the occupant behaviour may be very different. Table 1 lists some examples of differences between offices and dwellings, which influence possibilities of coping with high temperatures in summer. These possibilities for interacting may not apply during night when occupants are asleep. Therefore the bedroom and children's room may need to be considered as more critical rooms with a greater need for comfortable temperatures, more similar to an office situation. In relation to hours of too high temperatures, the night situation is however less critical as extra airing during night with colder external air with lower temperature will often help resolve the too high temperature issue. If it is not possible to keep the windows open during night, this can pose a problem.

Table 1. Examples of differences between offices and dwellings that influence possibilities of coping with a too high summer temperature

Office	Dwelling
Fixed workplace	Free to move to a less hot room or to go outside
Dress code	Free to change to less warm clothing
Limited possibility of changing ventilation rate	Free to open windows/doors
Solar shading may be controlled simultaneous in large sections of the building	Free to activate solar shading to protect from direct sun and glare
High expectation to work performance	More flexible expectation to performance

In dwellings a higher temperature due to solar gain in the spring and autumn may be perceived as beneficial as it will reduce the expense for heating, which will benefit the owner. Therefore, occupants may actually appreciate high temperatures during these seasons. Occupants may also react differently in dwellings due to psychological effects that can make it either easier or harder to cope with too high temperatures.

Table 1 shows some examples where there is more flexibility in dwellings than in offices even though standards suggest the same limitations. BR10 only regulates the summer temperature in dwellings but for other building types BR10 prescribes that it is up to the developer to specify requirements for temperature conditions in summer. Therefore, it can be discussed if the limits of maximum 100 hours a year above 26 °C for dwellings are reasonable and if the temperature requirements should be the same for all rooms.

The results of the survey seem to indicate that the BR10 requirement for documentation of temperature in summer for dwellings helps to ensure that common sense is incorporated in the design of new low-energy dwellings in Denmark. However, the survey also points out that the problem is not totally solved as temperature conditions in summer is still unsatisfactory for 19% on a daily basis and for 32% on a weekly basis. Therefore, the issue still needs to be addressed in the building design.

In the public hearing of the BR15, which is taking place as this paper is being written, it is suggested to raise the limits and change the requirements so that 27 °C must not be exceeded for more than 100 hours a year and 28 °C must not be exceeded for more than 25 hours a year. The change was initiated partly due to the implementation of a new reference year and feedback based on actual experience from the building sector, which found that the former temperature limits were too rigorous and consequently the temperature has been raised by one degree while the number of hours is maintained. This will preserve the link to the former limits in BR10. The effect of changing the reference year is that the outdoor temperature contains more hours above 27 °C.

In the design phase, it is suggested that documentation for complying with the BR10 requirements to thermal comfort in summer should be made by a simple calculation tool or by advanced simulation of the thermal conditions in summer. BR10 defines the operating hours of a dwelling to be 24 hours a day meaning that occupants are always assumed/expected to be at home and available to regulate the indoor climate by activating solar shading and increasing venting by opening of windows and doors. In practice, this is rarely the case so the predicted number of hours above 26 °C and 27 °C may not correspond to the actual presence in low-energy dwellings. The actual number of hours with too high temperatures in summer depends largely on user behaviour, and may mainly pose a problem at night when occupants want to sleep, rather than during the day.

The main focus of the demand for temperature limits is to ensure that there are sufficient opportunities for ventilation of the houses and suitable solar protection. With this in focus the results of the survey suggest that it is important to explain the ventilation principle of the dwelling to help users make good decisions to avoid too high temperatures.

This survey has shown that satisfaction with the perceived indoor climate has improved compared with previous studies on earlier generations of low-energy houses (Knudsen et al., 2012 and 2013). The results however indicate that there is a need for more knowledge of what can be considered as “acceptable” temperatures in dwellings. Such knowledge is also important for assessing what can be considered as acceptable temperature variations to take advantage of the house for heat storage in a possible future “intelligent” energy system.

Earlier studies have also called for robust and easy-to-use technical installations that are fully operational at the time of moving into the house. Comparing the results of this study with similar studies on earlier generations of low-energy houses (Knudsen et al., 2012 and 2013), it was found that problems with the technical installations had decreased. However, there is still a need for continued focus on the commissioning of new and not necessarily thoroughly tested high performance installations and new designs in order to achieve both a good indoor climate and low energy consumption.

The results of the survey also indicate that there is a need for extra focus on annoying noise from the ventilation system in bedrooms as this is reported by 13% of the occupants. Therefore, it is important to focus on noise reduction in the ventilation system and especially at inlets in bedrooms and children’s rooms. In summer it can be useful to use night ventilation to cool down the house, which in turn can influence the dissatisfaction with the noise from the ventilation system in the bedrooms. This is an area that needs to be investigated further.

To a greater extent than previously, the house owners in this study experienced that their heat consumption was as low as they had expected before they moved into the new house. This might be due to improved communication with house owners giving a more realistic expectation of their energy consumption in accordance with their family situation and behaviour.

CONCLUSIONS

The majority of house owners were satisfied with their new low-energy houses, and would recommend others to live in a low-energy house.

The survey did not uncover any new specific problems in relation to the suggested ambitious low-energy class 2015 requirements. The result of the survey contributed to formulating the final version of the new BR15 which is scheduled to take effect from summer 2015.

Generally, house owners perceived the indoor climate as satisfactory and as better than in their former older and not low-energy dwelling. The overheating in summer of earlier generations of low-energy houses seems to have been partly solved by the low-energy class 2015 requirements, which give upper limits for the number of hours exceeding 26 °C and 27 °C on warm days.

The survey, however, showed that some occupants are still dissatisfied with high indoor temperature in summer on both a daily and a weekly basis, so this still needs to be addressed in the building design.

The survey also showed that some occupants are still annoyed by noise from the ventilation system in bedrooms, so this is also an area that needs to be addressed in the building design.

Training/education of owners of new low-energy houses can help them to understand how their behaviour can support the automatic regulation of their indoor climate and energy consumption. In new dwellings, there are several possibilities of regulating the indoor climate but that may not apply during night when occupants are sleeping. Therefore, bedroom/children's room may need to be considered as a more critical room than the rest of the house which need special attention during the design of the house.

Occupants have different possibilities of coping with too high summer temperatures in dwellings and offices. There is a need for more knowledge about what can be considered as acceptable temperatures in dwellings. Until then the pragmatic solution applied in BR15 seem to help with handling the problem with overheating as building designers are forced to consider the consequences of their design choices in relation to high summer temperatures and solar radiation.

There is a need for continued focus on the commissioning of new low-energy houses so high-performance installations and new designs function as expected in order to ensure a good indoor climate and low energy consumption.

To a greater extent than previously, the house owners did experience that their heat consumption was as low as they had expected before they moved into their new house.

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