# Model Home 2020 – full-year measurements of daylight, energy and indoor climate in five single-family houses occupied by typical families: what has been learned


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## ABSTRACT

This paper describes Post Occupancy Evaluation survey and physical measurements of five families living for one year or longer in five houses located in Germany, Austria, France and UK, all part of the Model Home 2020 project. The houses are built according to Active House principles and focus on high performance on indoor environmental quality, energy performance and environmental impact. The survey is carried out seasonally during the test year when the family lives in the house to capture seasonal variations. Physical measurements were made in all main rooms of the houses. The houses have high daylight levels, which is highly appreciated by the families. High daylight levels increase the risk of overheating, but this has been avoided by design and control as the families do not report overheating, and as the houses in general achieve category 1 for the summer situation according to the Active House specification. The families also indicate high satisfaction with the general indoor environment and the indoor air quality, better health, fewer sick days and improved sleep quality that their expectations often are fulfilled, and that house automation is acceptable. The physical measurements support the importance of building automation in order to achieve good performance.



## KEYWORDS

Daylight, Thermal Comfort, Indoor air Quality, Dwellings, Post Occupancy Evaluation


## 1 INTRODUCTION

During 2009-2011, a demonstration project programme of five model homes were built in Denmark (Home for Life, HFL, 2009), Austria (Sunlighthouse, SLH, 2010), Germany (LichtAktiv Haus, LAH, 2010), France (Maison Air et Lumière, MAL, 2011) and United Kingdom (CarbonLight Homes, CLH, 2011). All houses are designed following the Active House principles (Active House, 2011) with the three main elements: Comfort, Energy and Environment. The houses have been occupied by test families in periods of one year or longer and have been tested and monitored in use, under post occupancy evaluation schemes by national research teams of engineers and/or scientists (Feifer et al., 2014).

The Active House principles mean that a balanced priority of energy use, indoor environment and connection to the external environment must be made. The design has particularly focused on high performance of the indoor environment as well as on a very low energy demand. There is a particular focus on good daylight conditions and fresh air from natural ventilation. The thermal environment in the houses has previously been reported (Foldbjerg et al., 2014).

Use of natural ventilation for summer comfort is based on ventilative cooling principles, referring to the use of natural or mechanical ventilation strategies to cool indoor spaces. This effective use of outside air reduces the energy consumption of cooling systems while maintaining good thermal comfort (venticool, 2015). To ensure fresh air supply, the houses use natural ventilation in the warm part of the year and uses mechanical ventilation with heat recovery during cold periods. The exception is LichtAktiv Haus, which is a renovation project, using natural ventilation all year. There is external automatic solar shading on windows towards south and in most cases also towards east and west. Overhangs are used where appropriate.

# 2 METHODOLOGIES

## 2.1 Physical Measurements

Measurements of Indoor Environmental Quality (IEQ) include light, thermal conditions, indoor air quality, occupant presence and all occupant interactions with the building installations, including all operations of windows and solar shading. Each room is an individual zone in the control system, and each room is controlled individually. There are sensors for humidity, temperature, $CO_2$, presence and lux in all main rooms, used for both control and data recording. The building occupants can override the automatic controls, including ventilation and solar shading at any time. The recorded temperature data is evaluated according to the Active House specification (Active House, 2011), which is based on the adaptive approach of EN 15251 (CEN, 2007).

## 2.2 Post Occupancy Evaluation Survey

As part of the evaluation, a Post Occupancy Evaluation (POE) survey is carried out seasonally during the test year allowing to capture and explore variation on a seasonal basis with approximately three months in-between. The intent with four replies per house is twofold. Firstly, this is to identify if the occupants experience their perception changes during the stay; for instance – is their perception of indoor environment, expression, comfort or automation changing through their stay. The second aspect to the seasonal distribution is to explore if seasonal changes in weather (e.g. outdoor temperatures, daylight) influence occupant experience.

The questionnaire is translated into native language. It is a set of questions relating statements about satisfaction/dissatisfaction with energy consumption and production, indoor climate and air quality, daylight and electric lighting, house automation, and sustainability. Also addressed is the frequency of occupant interaction with elements of the house, and if the house fulfil expectations of the occupants (Olesen, 2014). In this study, the advantage of using a questionnaire is that it is easier to distribute several times, but the disadvantage is the limited number of houses studied, and thereby statistical tools that can be used to draw significant conclusions from the survey. Each family in four of the houses (HFL was not included) responded to the questionnaire four times during a year (at 3-month intervals) with two additional responses from CLH. In total 18 responses were made.

The questions about satisfaction were made as sets of Likert-scales categorised as *very satisfied*, *satisfied*, *neither satisfied nor unsatisfied*, *unsatisfied*, and *very unsatisfied*. Questions about how comfortable the subjects are in their indoor environments are categorised on a five-point rating scale by: *very rarely, rarely, occasionally, frequently, and very frequently*. Finally, the questions about energy, environment and sustainability were made as sets of statements and categorised as a three-point scale *yes, very, yes to some extent, no normally not*, or as sets of five-point scales *strongly agree - strongly disagree*, and *very good – very bad*.

The overall purpose of the evaluations is to get indications on how successful the houses are, if there are challenges or problems, and what can be learned and improved.

## 3 RESULTS

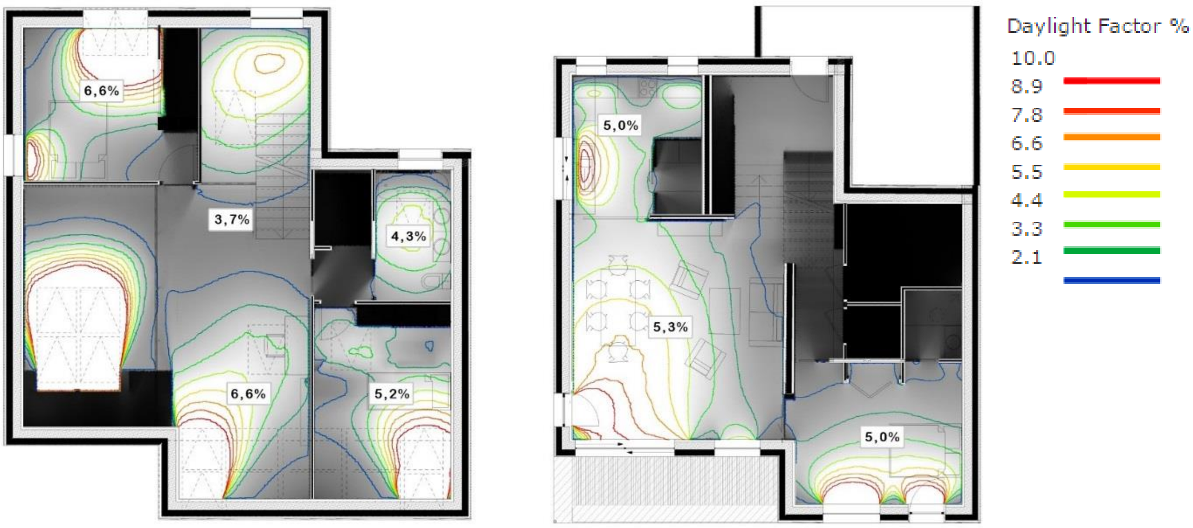
Generally, in the Post Occupancy Evaluation survey the indoor climate is rated as "very important" and the residents state most of the time that it is "good" or "very good" (>90% state "good" or "very good").

### 3.1 Improved sleep, reduced number of sick days and emphasis on view out

The POE survey found that the families experience that their sleep quality compared to their former home is "better" (50%) or "almost the same" (39%), and when rating their children's sleep quality, the tendency is a bit higher ("better" 56%; "almost the same" 44%). Furthermore, they have a significant experience that they have "less" sick days (83%) than in their former home, and they state their general health all in all as "good" or "very good". View to the outside through the window is rated as "very important" (44%) or as "quite important" (50%). Between 72% and 83% of the residents reported that they were "satisfied" or "very satisfied" with the view in the house in general.

### 3.2 High daylight levels without overheating

All of the houses were designed for good daylight conditions, expressed by a target average daylight factor of 5% or higher in the main rooms. This was generally achieved, with only insignificant deviations. In the POE survey, the daylight levels in the houses is rated either as "much higher" (88%) or as "higher" (12%) than their former home. The families report that the daylight level is generally "appropriate" (>75%) in the kitchen, the living room, and the bedroom. Between 89% and 100% of the residents reported that they were "satisfied" or "very satisfied" with the daylight in the house in general. They also state the windows are "about right" for all the rooms (>89%).




1st floor Ground floor

Figure 3. Daylight calculation. The amount of daylight and the quality of its distribution in Maison Air et Lumière have been evaluated using VELUX Daylight Visualizer 2.

Good daylight conditions come with the potential risk of overheating, as plenty of sunlight also provides plenty of solar gains, which can lead to overheating in summer and intermediate seasons. The results from all houses show that overheating has been prevented. That is demonstrated by the fact that the buildings achieve category 1 according to the Active House specification for thermal comfort during summer (in less than 5% of the hours of the year the temperature is above category 1). See example of temperatures in Figure 1 from Sunlighthouse.

This is well in line with the POE survey, as the residents in all houses are either "very satisfied" or "satisfied" with the temperature conditions in general (90%). Most of the time, the temperature conditions is assessed as about right, but separated into the different seasons of the year, the winter and the spring/autumn is stated as time of the year when the temperature is sometimes evaluated as varying, while few state temperatures as too hot, even in the summer.

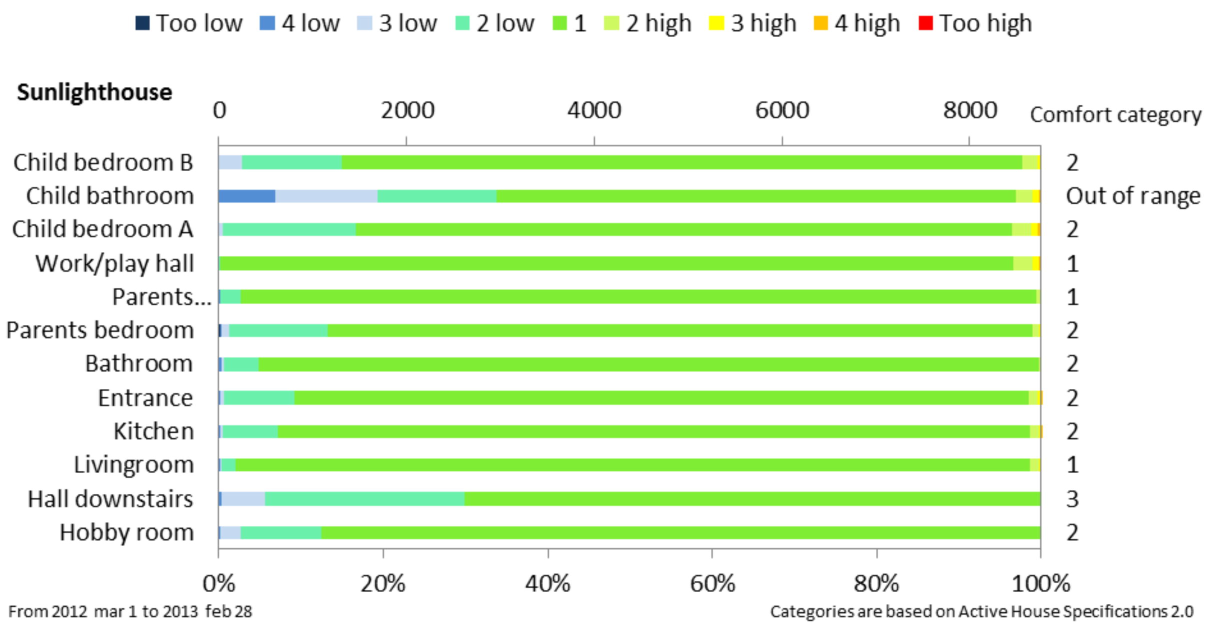



Figure 1. Thermal comfort of Sunlighthouse for each of the rooms evaluated according to Active House specification (based on adaptive method of EN 15251). Criteria are differentiated between high and low temperatures.

### 3.3 Electric light is not used between sunrise and sunset

The families state in the POE survey that they turn the electric light on "less often" (100%) than in their former home, and they evaluate the light levels as "appropriate" (>72%) in the focus rooms.

The measurements support this and show that electric light is generally not used between sunrise and sunset. This is the case not only during summer, but also during the darker winter months. This can be expressed by the term *daylight autonomy* (Reinhardt, 2001): Rooms can be expected to be daylight autonomous when the average daylight factor in a room is above 5%. The results support this.

### 3.4 No night-time overheating in bedrooms

Only limited research has been identified on the relation between temperature and sleep quality, but what is known is that the temperature in bedrooms during the night should not be *too high*, to prevent reduction of sleep quality (Laverge et al., 2011). In lack of a better threshold, category 1 is used as indicator of acceptable temperature for sleeping.

The time-of-day when the few annual hours with temperatures above Active House category 1 occur in the houses, have been identified. These hours occur in the afternoon. After sunset, the temperature drops to category 1 again with the exception of a few days per year in each house. This indicates that the houses have provided a thermal environment that did not pose a risk of reduced sleep quality. See Figure 2 for an example from the master bedroom in LichtAktiv Haus.

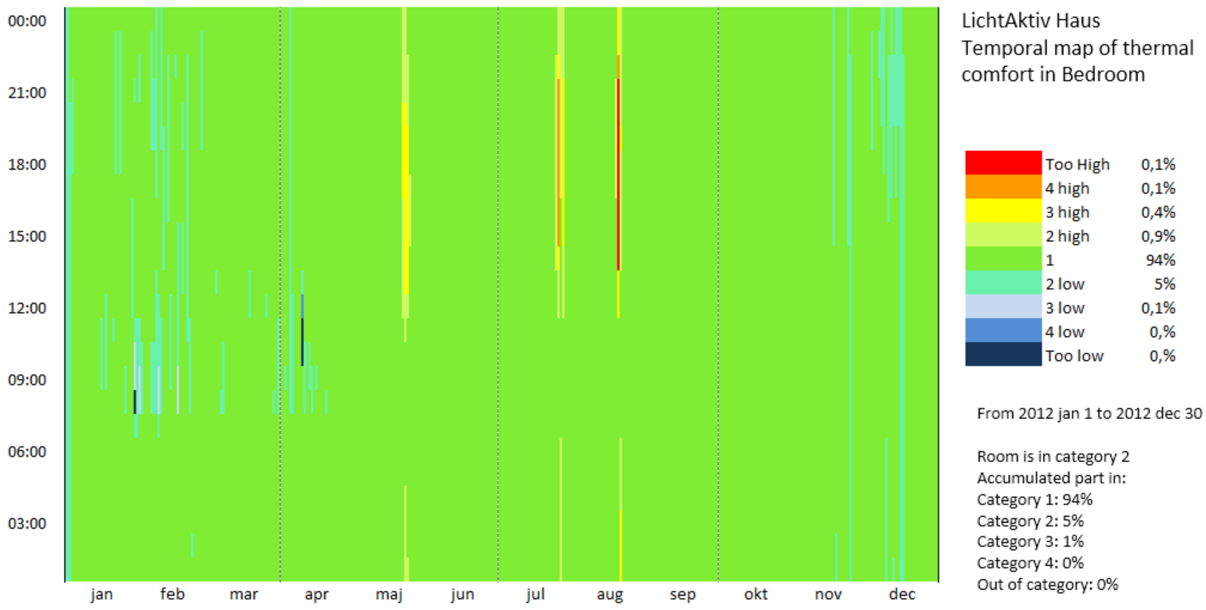



Figure 2. Thermal comfort of the master bedroom in LichtAktiv Haus. Each of the hours of the year are illustrated as a small square. The hours are presented so that hours of the same day are sorted from 00:00 to 24:00 (bottom to top), and from January to December (left to right). The few hours with temperatures above category 1 are seen as yellow, orange or red colour. These hours occur during three periods, each of 3-4 days. They begin around 13:00 and in most cases, the temperature has dropped to category 1 or 2 again before 22:00. During the night from 24:00 to 6:00 there is practically no hours with temperatures above category 2.

### 3.5 Ventilative cooling by natural ventilation prevents overheating. Night cooling is important.

A particular element of the present study is that the actual position of windows and solar shading has been included in the data recording, which provides detailed insights on the role of these components. The use of window openings follow the seasons; during spring and autumn windows are used on most days for approx. 50% of the time during daytime. During summer, windows are used more systematically during daytime hours, and also during the night. There is a correlation between the use of windows and hours without overheating. This is an indication that window openings have played an important role in maintaining good thermal comfort. See Figure 3.

Open windows during the night (night cooling) cools down the rooms from a temperature at the upper range of the comfort range to a temperature at the lower end of the comfort range, e.g. from 26°C in the evening to 20°C in the morning. The temperature can then rise during the day, in many cases without becoming uncomfortably hot at the end of the day. This underlines the importance of night cooling.

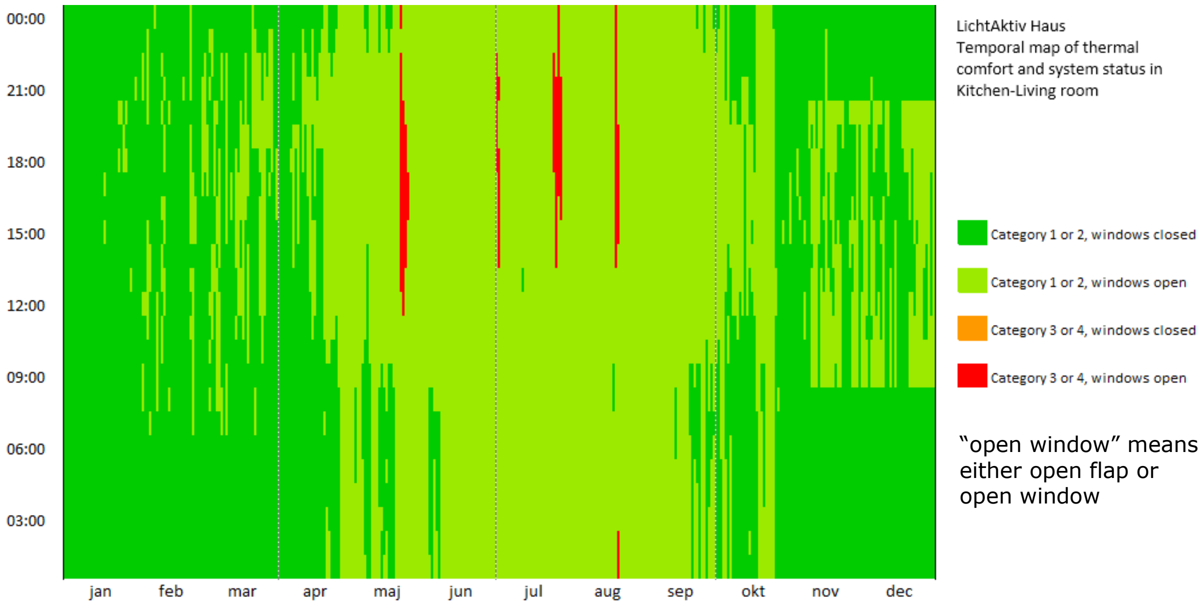



Figure 3. Thermal comfort of the kitchen/living room in LichtAktiv Haus, similarly as in Figure 2. On this figure, categories 1 and 2 are bundled, as well as categories 3 and 4. The position of windows is added (open or closed). The result is an illustration of when windows were open, and the relation to the thermal comfort at the same time. The light green squares represent hours when windows were open and good thermal comfort occurred; this happened during daytime in spring and autumn, and during the night in summer.

The results are supported by tracer gas measurements, which were used to investigate the airflow generated by ventilative cooling, and how large a temperature reduction ventilative cooling provided. The results showed that airflow rates of 10-20 air changes per hour could be achieved, and that the indoor temperature could be maintained 5°C lower than if ventilative cooling had not been applied (Favre et al., 2013).

### 3.6 Solar shading helps prevent overheating

The position of solar shading was recorded just as the position of windows. Awning blinds were the preferred type of external shading used on the houses, and the results show that the awning blinds had a role in providing good thermal comfort. The awning blinds were used the most during the summer, but also during spring and autumn. There is a correlation between use of awning blinds and hours without overheating.

### 3.7 Automation important

Automated control of window openings, solar shading and mechanical ventilation was used in all the investigated houses. The results show that solar shading and window openings are used frequently during work-hours on weekdays and during the night, e.g. at times when the families cannot be expected to be able to operate the products themselves. The same use of products could not have been achieved with only manual products.

The families respond in the POE survey that they are generally "very satisfied" or "satisfied" (>85%) with the way the house system operates the facade and roof windows, the indoor temperature, internal and external screen, and ventilation system (one house is solely naturally ventilated). They have a clear feeling that the way the control unit operates the house support their needs, and is either "easy" or "very easy" to use. It further shows that they "rarely" or "occasionally" use the control system to manually operate the facade and roof windows, internal temperature, but more frequently use the control system to operate the screening.

### 3.8 Satisfying $CO_2$-levels during summer

The $CO_2$ levels are low during the spring, summer and autumn seasons, typically below 900 ppm. Natural ventilation is used in this period as the only mean of ventilation, and the results clearly shows that with limited temperature difference to drive the stack effect, it is still possible to reach a reasonable level. During summer there is no electricity consumption for mechanical ventilation and no heat loss, so high ventilation rates and excellent indoor air quality can be achieved without any use of energy. It is also shown that openable windows were generally able to reduce or maintain low $CO_2$ levels in all the Model homes 2020.

The most challenging rooms are the bedrooms, as these are small rooms where approximately eight hours are spent each night, often two persons together in the same room. This is longer time than we spend in any other room in the home. Still, the $CO_2$-levels are maintained at a reasonable level in the bedrooms. Figure 4 is an example of the $CO_2$-level in a bedroom in Maison Air et Lumière.

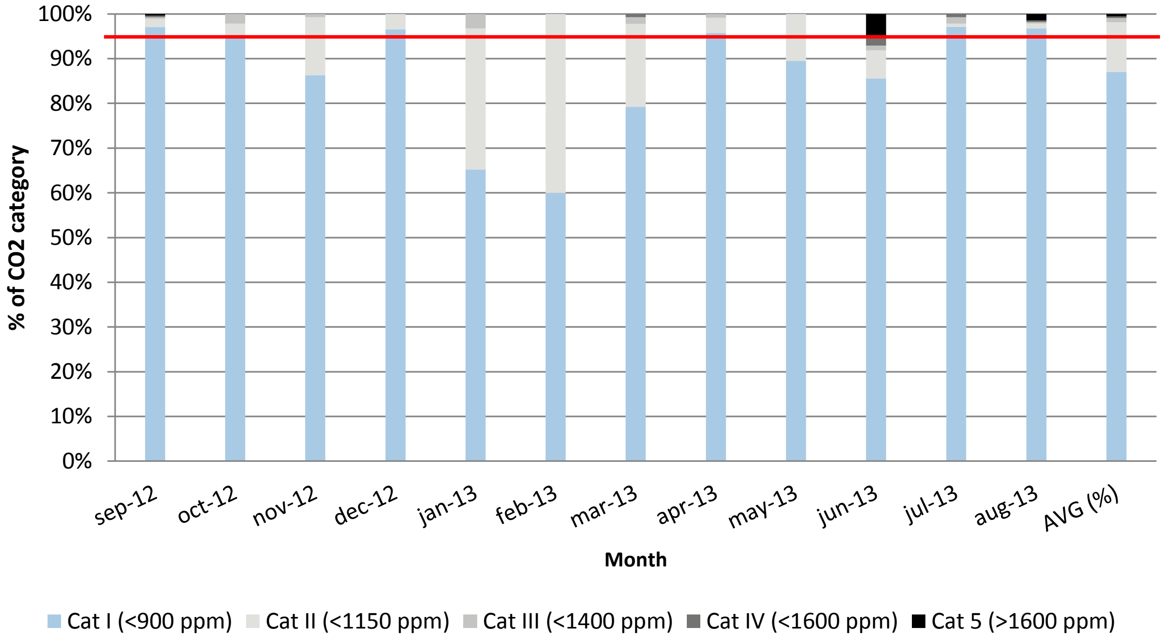



Figure 4. Bedroom in Maison Air et Lumière. Monthly distribution of night time hours in each of five categories for $CO_2$ level, based on Active House specification. The $CO_2$-level is lower during the summer than in winter.

The POE survey indicates that the perceived indoor air quality is good as it is rated as "very acceptable" (78%) or "acceptable" (22%), and the families state that they have not experienced any problems at all. If they want to improve the air quality, they open the facade and roof windows, and make airings. In most of the houses there is hybrid ventilation, so that mechanical ventilation with heat recovery is used during the winter to save energy. The mechanical ventilation systems are designed and commissioned to provide the ventilation rates required by the building codes, and they fulfil this requirement flawlessly. However, when the winter $CO_2$-levels are evaluated according to the Active House specification, particularly bedrooms only achieve a score of 2 or 3.

## 4 CONCLUSIONS

The five houses have good daylight conditions (DF > 5% in main rooms), and the results show that electric light under these conditions was not used between sunrise and sunset. The measurements show that good daylight conditions can be obtained without causing overheating, when solar shading and window openings are included in the building design and controlled automatically. Night cooling is a particular important aspect. It was found that high ventilation rates can be achieved also during summer with limited temperature difference available as driving force.

The use of ventilative cooling during summer also meant that the ventilation rates were high in this period, and as a consequence the measured $CO_2$-levels were low. The POE survey indicated that the families show high satisfaction with the indoor environment, that their expectations often are fulfilled, and that house automation is acceptable. Furthermore, combining excellent indoor environment with high quality homes, gives a clear indication that the residents experience better health and better sleep quality, as well as having less sick days than when living in their former homes.

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