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

Peter Foldbjerg*, Thorbjørn Færing Asmussen, Christoffer Plesner, Jens Christoffersen
VELUX A/S,
Ådalsvej 99
DK-2970 Hoersholm
Denmark
*Corresponding email: peter.foldbjerg@velux.com

Abstract

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

Introduction

The Model Home 2020 project is a vision for climate neutral buildings with a high degree of liveability. The intention of the Model Home 2020 strategy was to combine an excellent indoor environment with high quality homes mainly driven by renewable energy sources, as contextually optimized design solutions. Each building in the project was designed to reflect and respond to the different climatic, cultural and architectural conditions of the countries in which they were built. During 2009-2011, a demonstration project programme of five model homes were built in Austria (Sunlighthosue, SLH, 2010), Germany (LichtAktiv Haus, LAH, 2010), France (Maison Air et Lumière, MAL, 2011) and United Kingdom (the twin houses CarbonLight Homes, CLH, 2011) (see Figure 1 and Figure 2). All houses were designed following the Active House principles (Active House, 2011) with the three main elements: Comfort, Energy and Environment. The houses were occupied by test families in periods of one year or longer, and were tested and monitored, whilst in use, by national research teams of engineers and / or scientists (Feifer et al., 2014).

The Active House principles mean that balanced priorities of energy use, indoor environment and connection to the external environment must be made. The design was particularly focused on the high performance of the indoor environment as well as a very low energy demand. There was 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).

Model Home 2020

LichtAktiv Haus was built in 2010 and the family moved in during December 2011. LichtAktiv Haus was the first CO_2-neutral modernisation of a so-called Siedlerhaus, a semi-detached house from the 1950s located in the Wilhelmsburg district of Hamburg. The innovative modernisation strategy combined maximum liveability with optimum energy efficiency. The once tight and closed structure of the building was transformed into spacious rooms with high levels of daylight, providing occupants with the best living comfort. Natural ventilation ensures a healthy indoor climate. The refurbished house contained two children's rooms, two bathrooms, a master bedroom, a central living area and a reading room. All rooms featured façade and roof windows that were positioned to ensure optimum distribution of daylight. The floor area of the house was 185 m^2 and the glass area was equivalent to 58 % of the floor area. To provide electricity and hot water, solar collectors and photovoltaic solar cells were used – everything to cover the energy demands of the house.

Figure 1. Exterior photo of the five single-family houses, Model Home 2020. *LichtAktiv Haus (Germany) is upper left, Sunlighthouse (Austria) is upper right, Maison Air et Lumiére (France) is lower left and the Carbon Lighthouse (UK) is the lower right (Photo by Adam Mørk).*

Sunlighthouse was built in 2010 and the family moved in, in February 2011. Sunlighthouse is Austria's first carbon-neutral, single-family home. The vision was to build a house with exciting and appealing architecture, focusing on the sloping roof. The house aimed to be generally affordable and to meet certain specifications of dimensions, material and appearance. Sunlighthouse provided an exceptionally high proportion of daylight and achieved a positive energy balance during the test period, by reducing its overall energy consumption and by using renewable energy. The net floor area of the house was 201 m2, and the total window area was equivalent to 51 % of the net floor area.

Maison Air et Lumière was built in 2011 and the family moved in during September 2012. Maison Air et Lumière is a new generation of active homes that puts the quality of life of its inhabitants at the centre of its environmental approach. The unique features of the house lie in intelligent use of the sloping roof to combine well-being and energy efficiency. The architectural concept was based on different roof pitches that increased its ability to capture sunlight, making it an energy-positive home. The pitched roof is part of France's cultural heritage. Roof pitches vary in steepness according to region and climate – and to meet the need for light and solar gain. Carefully positioned façade and roof windows allow sunlight from all directions. The windows also enable the space to be filled with fresh air, to ensure a comfortable living environment all year long. The 130 m² floor area extends to over one and a half storeys, with the spaces under the roof put to full use, and a window-floor ratio of nearly 1:3.

Figure 2. Interior photo of the five single-family houses, Model Home 2020. *LichtAktiv Haus (Germany) is upper left, Sunlighthouse (Austria) is upper right, Maison Air et Lumiére (France) is lower left and the Carbon Lighthouse (UK) is the lower right (Photo by Adam Mørk).*

The CarbonLight Homes were built in 2011 and the families moved in, during January 2013 and April 2013. CarbonLight homes are the first new homes in the UK designed and built to the new UK Government definition of zero carbon and were set to achieve a level 4 of the Code for Sustainable Homes. They are designed to be real homes for real people with construction techniques suitable for use by mass house builders. CarbonLight Homes use nature in an intelligent way to maximise daylight and encourage a sustainable lifestyle. The design is open plan and incorporates high levels of daylight and natural ventilation, intended to minimise energy consumption among residents and generate a sense of community. The homes showed that common-sense design can be used to create inspirational sustainable houses that can be easily replicated by UK house builders. The net floor area of the houses is 230 m^2, and the glass area was equivalent to 24,5 % of the net floor area.

Methodologies

Physical Measurements

Measurements of Indoor Environmental Quality (IEQ) included light levels, thermal conditions, indoor air quality, occupant presence and all occupant interactions with the building installations, including all operations of windows and solar shading. All sensors were part of the building control system, so each sensor was used for both control and monitoring. The sensors for presence, temperature, CO2, relative humidity and light were standard sensors for control and not highly accurate. Their accuracy was evaluated with calibrated laboratory equipment before the start of the measurements. The sensors were wired to the control system. The recording of position of window and shading products was done by extracting data from the control system for these products.

Use of natural ventilation for summer comfort was based on ventilative cooling principles. Ventilative cooling refers 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 thermal comfort. The most common technique is the use of increased ventilation airflow rates and night ventilation (venticool, 2015). The houses used natural ventilation in the warm part of the year. The houses used mechanical ventilation with heat recovery during cold periods, except LichtAktiv Haus which is a renovation project, using natural ventilation all year. There was external automatic solar shading on windows towards the south and in most cases, also towards east and west. Overhangs were used where appropriate.

Each room was treated as an individual zone in the control system, and were controlled individually. The sensors, for humidity, temperature, CO_2, presence and lux in all main room, were used for both control and data recording. The building occupants could override the automatic controls, including ventilation and solar shading at any time. The recorded temperature data was evaluated according to the Active House specification (Active House, 2011), which is based on the adaptive approach of EN 15251 (CEN, 2007). The data from the sensors that were used for the controls of the houses, was recorded. The IEQ data was recorded for each individual zone as an event log, where a new event was recorded when the value of a parameter changed beyond a specified increment from the previously recorded value. The event log files were automatically converted into data files with fixed, 15-minute time steps, and used for the data analysis.

Post Occupancy Evaluation Survey

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

The questionnaire was translated into the occupants' native language and contained questions on satisfaction/dissatisfaction with energy consumption and production, indoor climate and air quality, daylight and electric lighting, house automation, and sustainability. Also addressed was the frequency of occupant interaction with elements of the house, and if the house fulfilled the expectations of the occupants (Olesen, 2014). In this study, the advantage of using a questionnaire was that it was easier to distribute several times, but the disadvantage was the limited number of houses studied, which thereby limits the statistical tools that can be used to draw significant conclusions from the survey. Each family in four of the houses (Home for Life, HFL was not included) responded to the questionnaire four times during the year, at 3-month intervals, with two additional responses from CarbonLight Homes, 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 were 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 from strongly agree to strongly disagree, and very good to very bad.

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

Results

The demographic questions about the family and their children (age between 0 and 9 years) showed that most of the residents had a working week away from the house (one family member works from home a few days per week). On weekdays, they normally spent between 11 to 16 hours in the house, while spending a longer time at home during the weekends (between 16 to 20 hours).

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

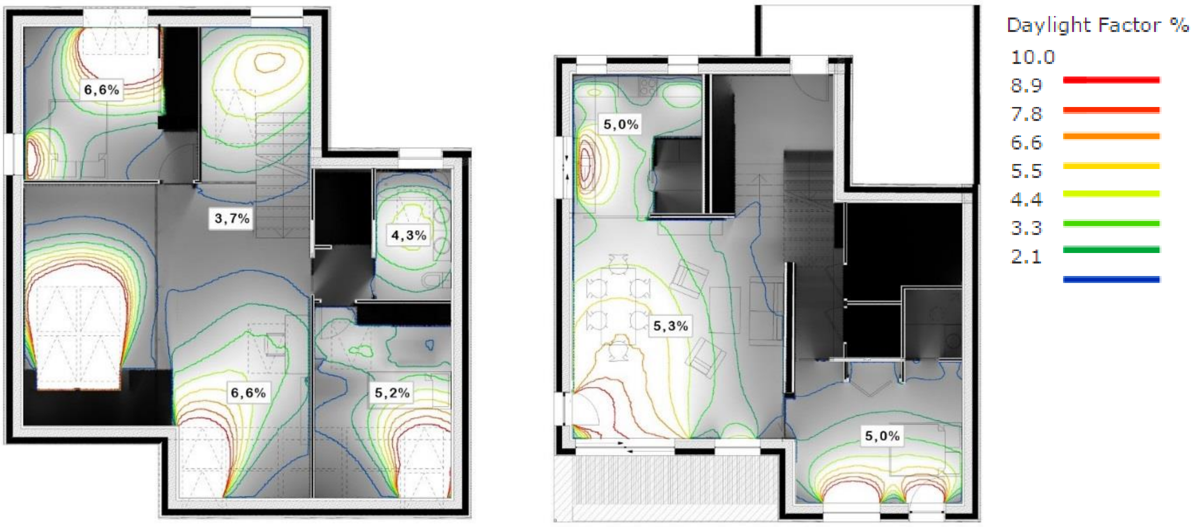
Within the last decade, increased knowledge has identified the importance of appropriate light during the day and darkness at night, as playing key roles in the regulation of the sleep/wake cycle (Veitch and Galasiu, 2012). Also, the room temperature when falling asleep has an influence on sleep quality and research suggests that it is preferable to have a lower room temperature during times of sleep than when awake. In the Model Homes 2020, the bedrooms had blackout blinds installed and the house control system allowed the possibility of remote window-opening. In the POE survey, the families were asked if they experienced their sleep quality as being "better, almost the same or worse" compared to their former home. They stated that they subjectively experienced sleep quality as being "better" (50%) or "almost the same" (39%), and when rating their children's sleep quality, the tendency was a bit higher ("better" 56%; "almost the same" 44%). Furthermore, they experienced "less" sick days (83%) than in their former homes and they stated that their general health, all in all, was "good" or "very good".

The view to the outside, through the window, was 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.

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. According to CIBSE (2002) with daylight levels of this magnitude, electric lighting will most likely not be used during daytime (see Figure 5). This was generally achieved, with only insignificant deviations. In the POE survey, the daylight levels in the houses were rated as being either "much higher" (88%) or "higher" (12%) than their former home. The families report that the daylight level was 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 their houses, in general. They also stated that the windows were “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 achieved a category 1 status, according to the Active House specification for thermal comfort, during summer. The temperature was above category 1 for less than 5% of all hours in the year. (See examples of temperatures in Figure 4 from Sunlighthouse.

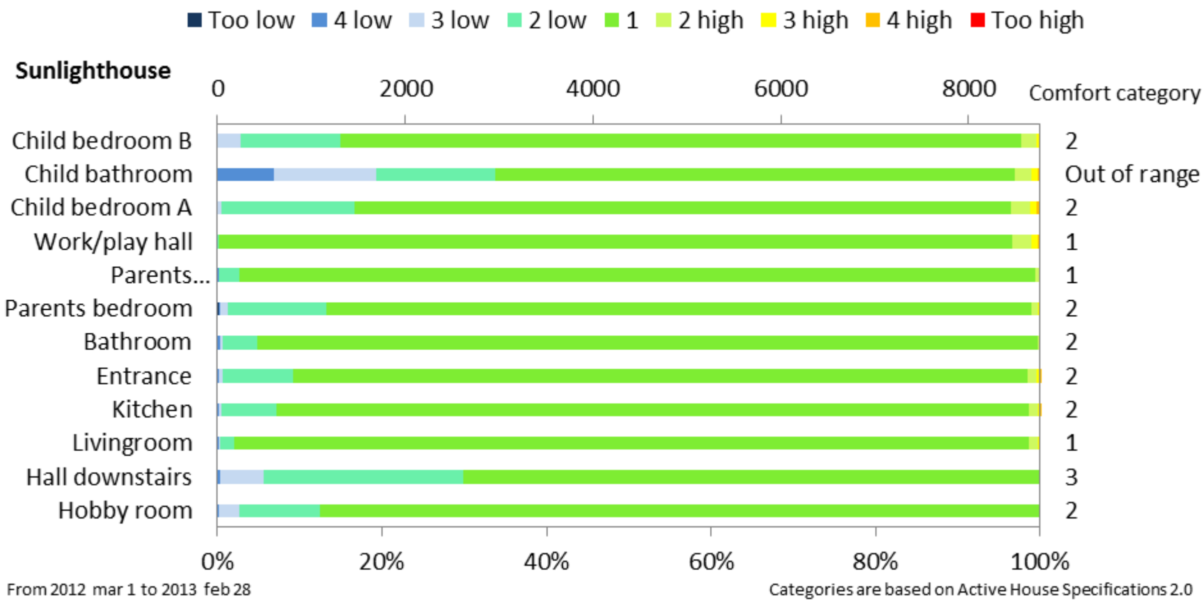


Figure 4. Thermal comfort of Sunlighthouse. *Thermal comfort for each of the rooms evaluated according to Active House specification (based on adaptive method of EN 15251). Criteria are differentiated between high and low temperatures.*

This is well in line with the POE survey, as the residents in all houses were either "very satisfied" or "satisfied" with the temperature conditions in general (90%). Most of the time, the temperature conditions were assessed as being about right, but separated into the different seasons of the year; the winter and the spring/autumn seasons were stated as being the time of the year with the largest temperature fluctuations. Only few respondents stated the temperature as being too hot, even in the summer.

Electric light is not used between sunrise and sunset

Between 67 and 89 % of the residents reported that they were "satisfied" or "very satisfied" with the artificial lighting in the house in general, for the three rooms in focus; the kitchen, the living room, and the bedroom. They stated that they turn the electric light on "less often" (100%) than in their former homes, and they evaluated the light levels as "appropriate" (>72%) in the focus rooms. Figure 5 shows the measured lighting use for a complete year in the kitchen of LichtAktiv Haus. In the morning, the lights were switched on in the winter months, when it was dark outside, while sufficient daylight in the summer months, limited the need for lighting use. For the evening lighting use, the temporal map shows a clear tendency of light switching after sunset, which suggests that the daylight level affected the switching probability, while outside weather and the day of the week had less impact. Similar switching patterns for the electric lighting use was found in the other houses

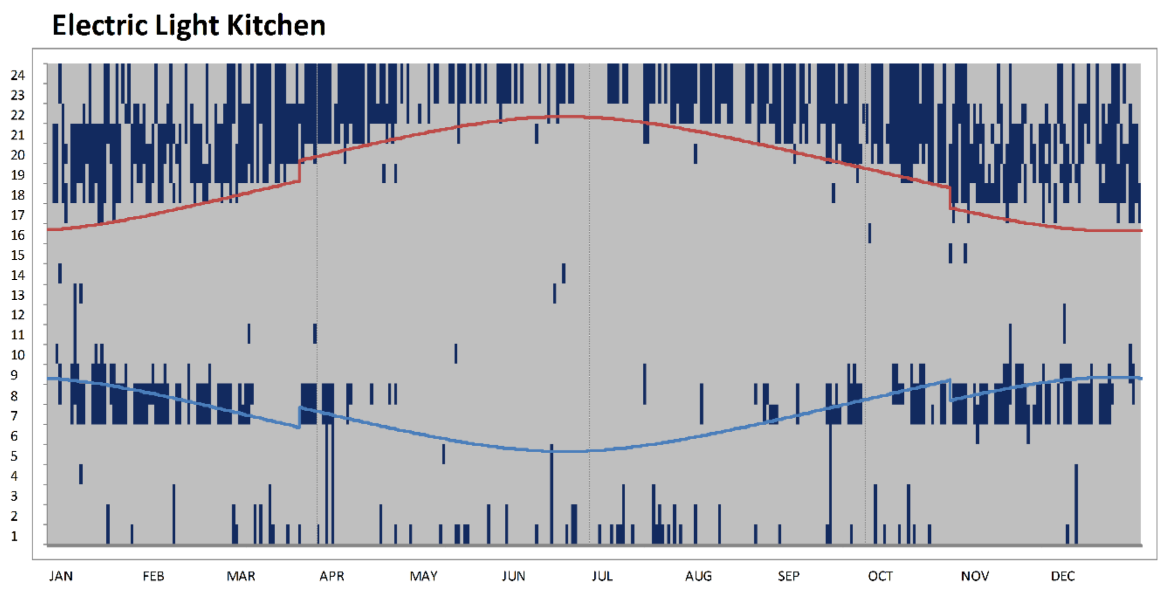


Figure 5 Temporal map of lighting use. *The dark blue colours mark the lighting use in the kitchen of LichtAktiv Haus. A temporal map, shows the day of the year mapped along the x-axis (January to December) and the time of day along the y-axis (0 to 24h). The two curves mark the sunrise (blue, upper) and sunset (red, lower), and the curves are adjusted according to local time and Daylight Saving Time (DST).*

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, as too high temperatures could impact, negatively, on" sleep quality (Laverge et al., 2011). For lack of a better threshold, category 1 is used as an indicator of acceptable temperature for sleeping.

The hours when the temperature rose above the category 1 were in the afternoon. After sunset, the temperature drops to a category 1 again, with the exception of a few days per year in each house. This indicates that the houses provided a thermal environment that did not pose a risk of reduced sleep quality. See Figure 6 for an example from the master bedroom in LichtAktiv Haus.

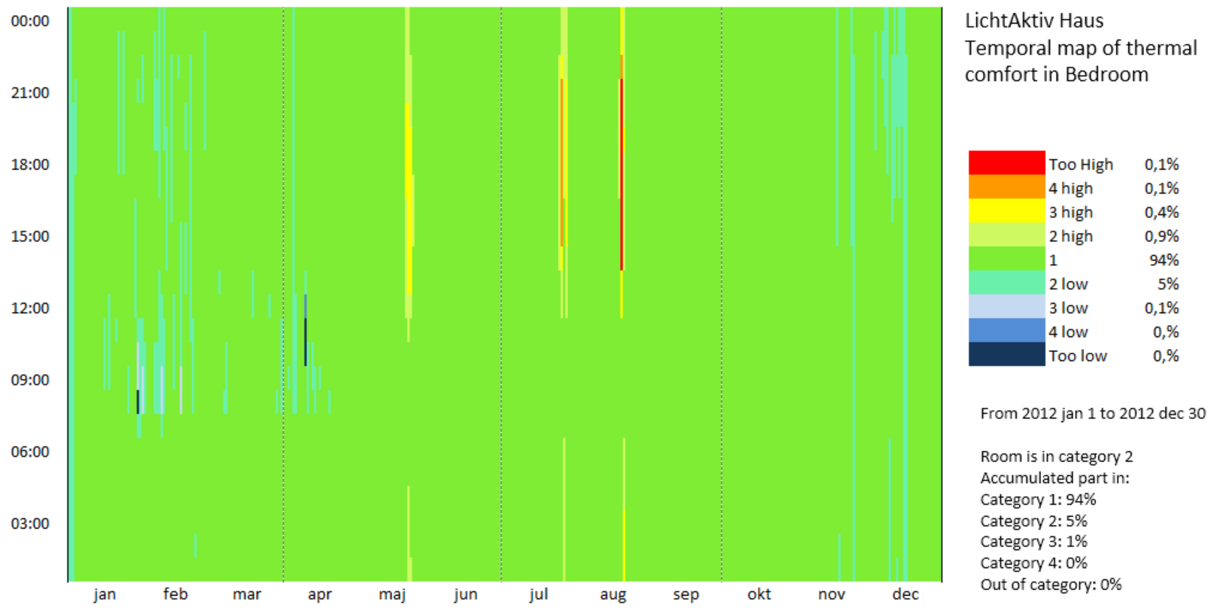


Figure 6. Thermal comfort of the master bedroom in LichtAktiv Haus. *Each hour of the year is illustrated as a small square. The hours are presented so that hours of the same day are sorted from 00:00 to 24:00 (bottom to top), and from January to December (left to right). The few hours with temperatures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

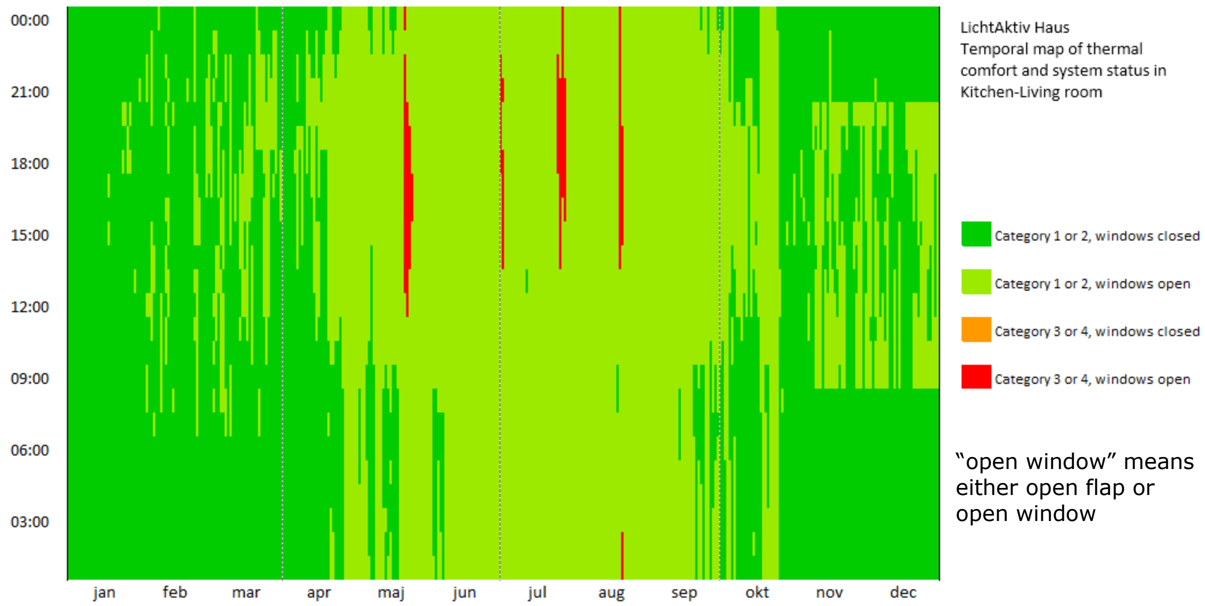


Figure 7. Thermal comfort of the kitchen living room in LichtAktiv Haus,*. In this figure, categories 1 and 2 are bundled, as well as categories 3 and 4. The position of windows is added (open or closed). The result is an illustration of when windows were open, and the relation to the thermal comfort 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 also during the night in summer.*

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 the level of solar shading have been included in the data recording, which provided detailed insights into the role of those components. The use of window opening followed the seasons; during spring and autumn windows were used on most days for approx. 50% of the time during daytime. During summer, windows were used more systematically during daytime hours, and also during the night. There is a correlation between use of windows and hours without overheating. This indicates that window openings have played an important role in maintaining good thermal comfort. See Figure 7.

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.

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).

Solar shading helps prevent overheating

The position of solar shading was recorded separately by extracting data from the control system. Awning blinds were the preferred type of external shading used on the houses, and the results showed 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 the use of awning blinds and the hours without overheating.

Automation important

Automated control of window openings, solar shading and mechanical ventilation were used in all the investigated buildings. The results show that the automated solar shading and window openings were 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 responded in the POE survey that they were generally “very satisfied” or “satisfied” (>85%) with the way the automated house system operated the facade and roof windows, the indoor temperature, internal and external screen, and ventilation system (one house used natural ventilation only). They had a clear feeling that the way the control unit operated the house supported their needs, and it was “easy” or “very easy” to use. The survey also showed that they “rarely” or “occasionally” used the control system to manually operate the facade and roof windows to regulate the internal temperature, but more frequently used the control system to manually operate the screening.

Satisfying CO2-levels during summer

Generally, the indoor climate was rated as “very important” and the residents stated that most of the time it was “good” or “very good” (>90% state “good” or “very good”). When the residents were asked to choose three conditions they would like to change to make the indoor climate more comfortable to live in, they reported less noise from the window opening systems, less peeping inside (privacy) and better electric lighting. The CO2 levels were low during the spring, summer and autumn seasons, typically below 900 ppm. Natural ventilation was used in this period as the only means of ventilation, and the results clearly show that the stack effect created by temperature and height differences with even a limited temperature difference, still made it possible to reach a reasonable CO_2 level. During summer there was 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.

The most challenging rooms were the bedrooms, as these were small rooms where approximately eight hours were spent each night, often two persons together in the same room. This is longer than the time spent in any other room in the home. Still, the CO2-levels were maintained at a reasonable level in the bedrooms. Figure 8 shows an example of the CO_2-level in a bedroom in Maison Air et Lumière.

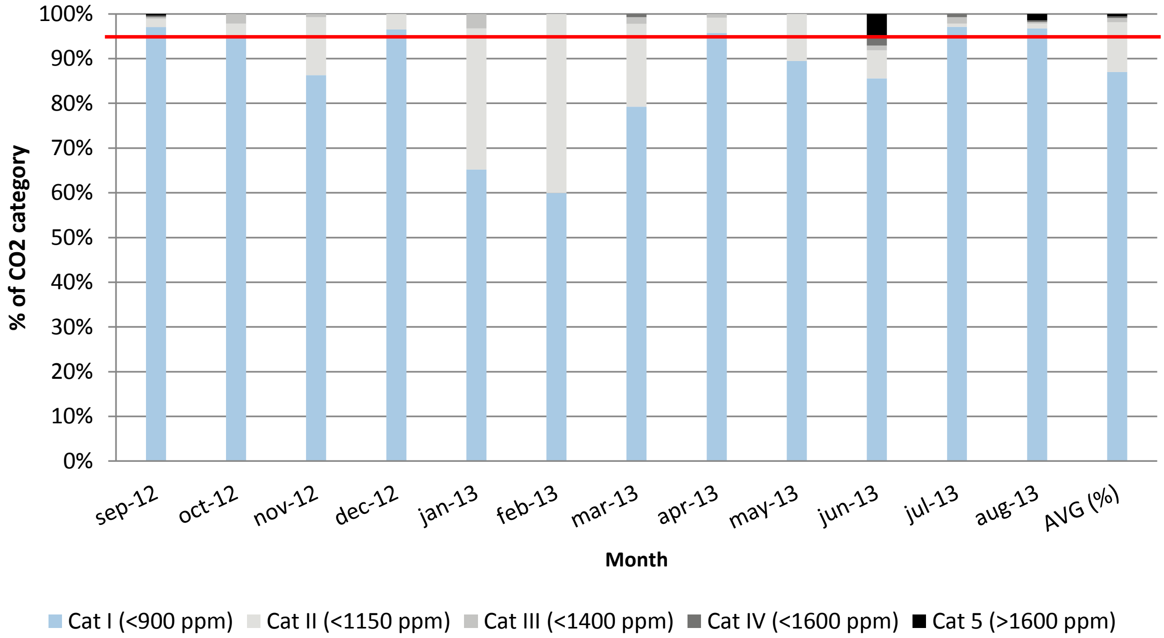


Figure 8. Bedroom in Maison Air et Lumière. *Monthly distribution of night time hours in each of five categories for CO_2 level, based on Active House specification. The CO_2-level is lower during the summer than in winter.*

The POE survey indicated that the perceived indoor air quality was good, as it was rated as "very acceptable" (78%) or "acceptable" (22%), and the families stated that they did not experience any problems at all. If they had wanted to improve the air quality, they could open the facade and roof windows to make airings. Most houses used hybrid ventilation, so that mechanical ventilation with heat recovery was used during the winter to save energy. The mechanical ventilation systems were designed and commissioned to provide the ventilation rates required by the building codes, and they fulfilled this requirement flawlessly. However, when the winter CO2-levels were evaluated according to the Active House specification, particular bedrooms only achieve a category 2 or 3.

Energy, environment and sustainability

The houses featured low-energy electric lighting, appliances and multimedia equipment – as well as photovoltaic cells integrated into the roof, solar collectors and air-to-water heat pumps. Measured energy performance of the houses are not dealt with in detail in this paper, since it differs as the houses are different and located in different climates. Instead, information about the calculated net energy demand and production is shown in Figure 9. As an example, the calculated heating requirement for the houses varied , such as 14.2 kWh/m² (Maison Air et Lumiére), 24.0 kWh/m^2 (Sunlighthouse), 57.6 kWh/m² (Carbon Lighthouse), and 63.0 kWh/m^2 for LichtAktiv Haus.

In general, the residents were, to some extent, conscious about their energy consumption, environmental impact of their daily behavior, hot water consumption, electric lighting use, and media attention on global warming regarding their energy consumption. Interestingly, living in these houses for one year did not make the family members more conscious about these topics over time, rather the reverse or they were indifferent. Most of the residents were aware, in their statements, that the PV panels and the solar thermal collectors do not produce the of the energy needed to produce electricity and hot water, although there was a tendency that the families were more aware of their hot water use at the end of their period living in the house. Among the residents, there were slightly different responses, but the tendency between the beginning and end of the year, showed similarities. The residents felt good about knowing that the house produces much of its own energy requirement, and that climate change had altered their behaviour, but they were more indifferent regarding spending on energy generating products. However, they liked the signaling value of the energy technologies used (PV panels and solar thermal collectors) and felt these technologies were well integrated in the design of the houses. They were generally “concerned” or “very concerned” about minding the environment as well as saving energy.

The residents felt that the location of the house, on site, was right and that the location in relation to daylight and sunlight was good. They did not find it too close to neighbours or roads. Their opinion on whether the house fitted into the neighbourhood was“yes, very” or “yes, to some degree” (88%), and they had fairly clear opinions that houses like these will be more common in the next 20 years. Their immediate impression of the house was of being futuristic and eco-conscious and good architecture, and they find it possible to include PV Panels and solar thermal collectors on architecturally attractive houses.

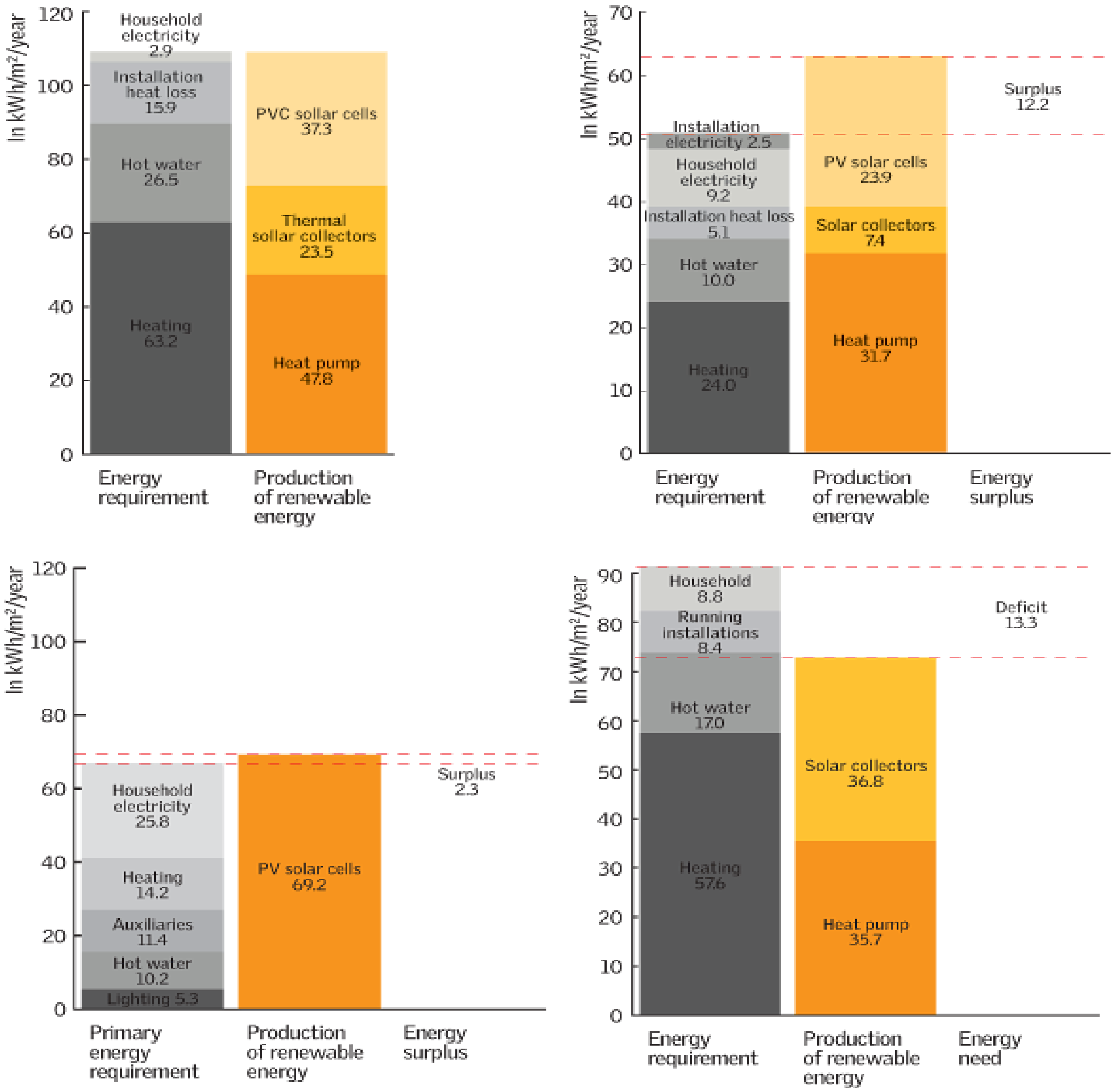


Figure 9. Energy performance and production. *The calculation of the energy performance and production has been made according to national standards. LichtAktiv Haus (Germany) is upper left, Sunlighthouse (Austria) is upper right, Maison Air et Lumiére (France) is lower left and the Carbon Lighthouse (UK) is the lower right.*

Conclusions

The five houses had good daylight conditions (DF > 5% in main rooms), and the results show that electric light under these conditions was rarely 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 particularly important aspect. It was found that high ventilation rates can be achieved also during summer utilizing the stack effect by ventilation through open façade and roof windows, even with the limited temperature differences that are available during the warmer period.

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 showed a few issues that could be improved, but generally indicated that the families showed high satisfaction with the indoor environment, that their expectations were often fulfilled, and that house automation was acceptable. Furthermore, combining an excellent indoor environment with high quality homes resulted in the residents experiencing better health and better sleep quality, as well as having less sick days, than when living in their former homes.

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