# Home, Smart Home

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# Home Smart Home: A Danish Energy Positive Home Designed With Daylight

By Ellen Kathrine Hansen, Gitte Gylling Hammershøj Olesen, and Michael Mullins

**ABSTRACT** | This paper focuses on how smart technologies integrated in a one-family home, and particularly a window, offer unique challenges and opportunities for designing buildings with the best possible environments for people and nature. Toward an interdisciplinary and multidimensional approach, we address the interaction between daylight defined in technical terms and daylight defined in aesthetic, architectural terms. Through field tests of a Danish carbon-neutral home and an analysis of five key design parameters, we explore the contradictions and potentials in smart buildings, using the smart window as an example of how quality of life and technical advances are synthesized and when they contradict. We focus on the need to define quantitative and qualitative values and synthesize these in a multidimensional design approach, toward allowing the house to adapt to a changing climate, satisfy the human needs of the occupants, together with meeting calculated energy requirements. Thus, integrating windows as key design elements in energy-positive buildings addresses aesthetic as well as technical potentials. This integration of factors from different fields can both support and counterbalance one another in the design process. We maintain that a hybrid approach to the energy design is central. The study illuminates an approach of the design of smart houses as living organisms by connecting technology with the needs of the occupants with the power and beauty of daylight.

**KEYWORDS** | Daylight design; experiment; green buildings; hybrid energy design; solar energy; sustainable development; sustainable smart architecture; windows

*"It has been interesting to experience that the house reacts—in some cases it even feels like the house acts as a direct function of human needs. The solar shading, for instance, closes just as we start to feel the need to rub our eyes and the skylight blinds come down just before the sun breaks through the clouds. If you did not know better you might think that the house was wired up to your nervous system."*

—*Anne-Mette, occupant [1]*

## I. INTRODUCTION

The popularity of smart homes, or home automation, has increased greatly in recent years due to the higher affordability and simplicity of the technology. This trend can be anticipated to gather pace following the widespread use of smartphone and tablet connectivity. Through the integration of information technologies with the dwelling environment, structures, components, and appliances are able to communicate interactively to enhance accessibility, energy efficiency, and safety. However, the ability to implement high-tech solutions to automation of functions in a home does not in itself ensure a higher quality of life. A hybrid design approach [3], which considers multidimensional solutions, remains an essential ingredient in achieving overall success.

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A fundamental design element in energy-generating and $CO_2$-neutral houses is the direct harnessing of the sun's energy. Smart management technologies with energy-efficient building components can enable dwellings to act like living organisms, detecting users' needs, sensing indoor and outdoor climatic conditions, and regulating the required supply of light and heat accordingly. Smart technologies can further contribute to an architectural freedom where beautiful spaces simultaneously create natural living environments and reduce energy consumption. A great challenge lies in integrating building components, control technologies, and user aspects, through a design thinking that focuses on both the qualitative and quantitative values inherent in good architecture.

The "hybrid" method is exemplified in the interdisciplinary design of a Danish experiment in building a carbon-neutral home [2], [3]. The dwelling was developed by the building industry in close collaboration with architects, engineers, and researchers. This paper explores the experiment with focus on the "smart window" as an example. We investigate how a smart window constitutes a multidimensional design element in the energy-optimized homes of the future, where living quality and technical improvements are synthesized in the design. We will focus on the complexity and contradictions in designing energy producing houses and the potential, or need, to define and synthesize the quantitative and qualitative values of a house that adapts like a living organism to changing climate conditions and the needs of the occupants.

To explore our vision, we use some of the qualitative data and experience collected on the indoor climate and energy use experienced by the occupants, during the two years that the house was occupied. In this paper, we describe the house, the technologies, the overall findings in the measurements, and the intentions through the design process. Then, we explore how the smart window can be employed as a multidimensional design element. Finally, we define contradictions and opportunities in designing with both qualitative and quantitative design parameters.

## II. HOME FOR LIFE—AN EXPERIMENT

Judging by looks alone, the simple one-and-a-half-story 190-m$^2$ house on a residential street outside Aarhus, Denmark, is an ordinary single-family home; see the photo of the house in Fig. 1. The stylish little house is a typical Scandinavian home. But this house is different. Looking carefully you will see that the house has a lot of window

**Fig. 1.** ***Home for Life: the south-facing smart window facade, the roof with integrated roof top windows, solar cells, solar heat panels, and the weather station on top of the roof. Photo by Adam Mørk.***

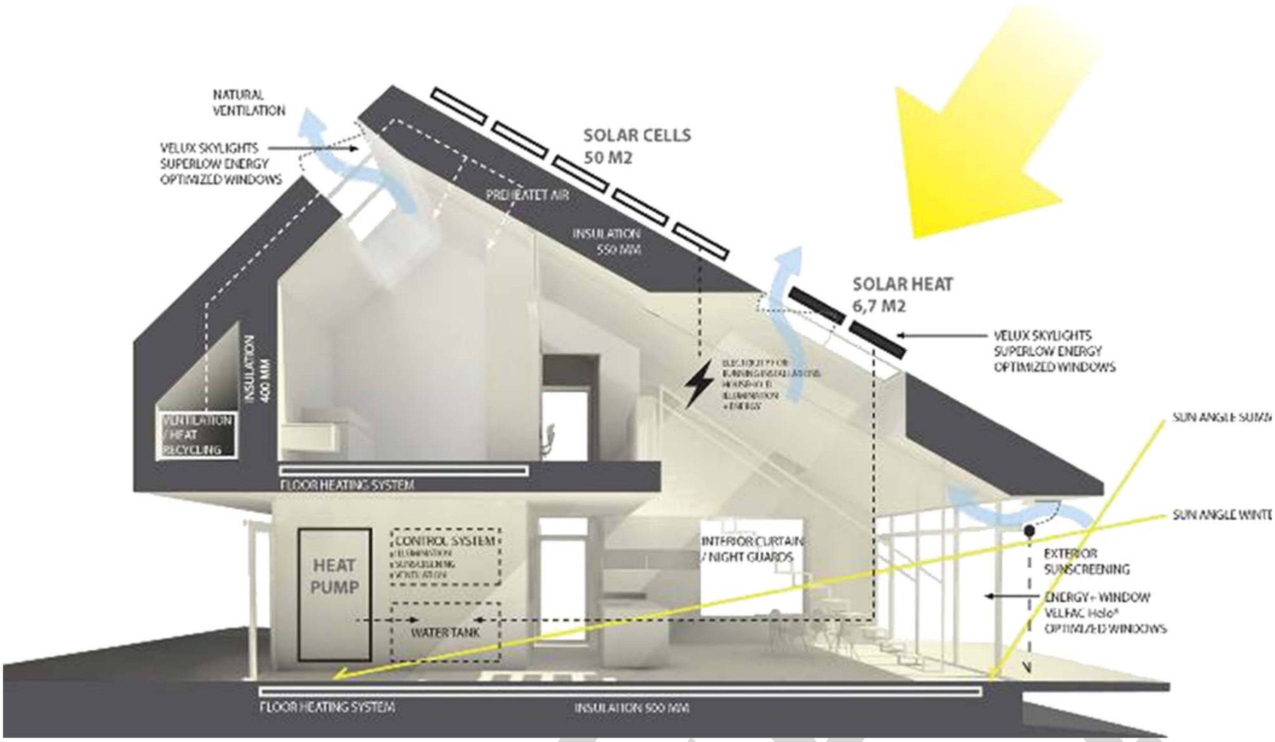


**Fig. 2.** ***Energy section illustrating the airflow for natural ventilation, the sunlight from summer and winter sun, the energy producing technologies on the roof, and the control system.***

area in all directions, a big south-facing roof with integrated solar panels, photo voltaic, and skylights, and a sort of an antenna on the top of the roof, which on investigation turns out to be a weather sensor. Smart components are compiled into an energy-optimized design: smart windows are carefully designed in a technical and architectural context. The house is designed to generate more than enough power to run itself, solely relying on the sun, while simultaneously creating spaces where one feels comfortable and may enjoy the daylight, fresh air, and close connection to the outdoors [7]; see Fig. 2.

The roof apex has been shifted toward the north, thereby creating a large south facing roof surface. On the ground floor, a central kitchen/dining room next to the west-facing living room emphasizes the large volumes created by the roof. On the first floor are bedrooms and the bathroom; these rooms, like all the rooms, have daylight from more than one direction and have access to balconies or terraces.

Smart facades and roof top windows, tight insulation, and a climate-control system minimize the need for electrical lighting and heating. The sun handles the rest: solar panels, solar thermal collectors, and the Home for Life's south-facing orientation allow the house to generate enough electricity and heat to make it carbon neutral. Moreover, energy calculations indicate that the use of building materials produced with less energy means that the emissions from their manufacturing will be negated within 40 years [4], [5].

The house was the first of eight experiments that the international window companies Velfac, Horsens, Denmark and Velux, Hørsholm, Denmark, together with their international sister companies Sonnenkraft, Tølløse, Denmark, and WindowMaster, Vedbæk, Denmark, have developed in five European countries [5]. The goal is to build a sustainable, affordable house that uses readily available technology to negate its imprint on the environment and to promote the health and comfort of its inhabitants through plenty of daylight and fresh air.

### A. Multidimensional Energy Design

As the project manager on this house, the first author worked closely with engineers, architects, and specialists from the window industry to ensure that every design decision took the overall vision into consideration—to create a house that did not use more energy than it gives back and, at the same time, has a good indoor climate with plenty of daylight and fresh air. Every technical requirement as well as architectural form was framed in terms of aesthetics, energy, and comfort. Various methods were used to communicate the aesthetic and technical elements, often with the smart window as a central element, including traditional architectural drawings, paintings, renderings and models, studies of scale models in light laboratories,

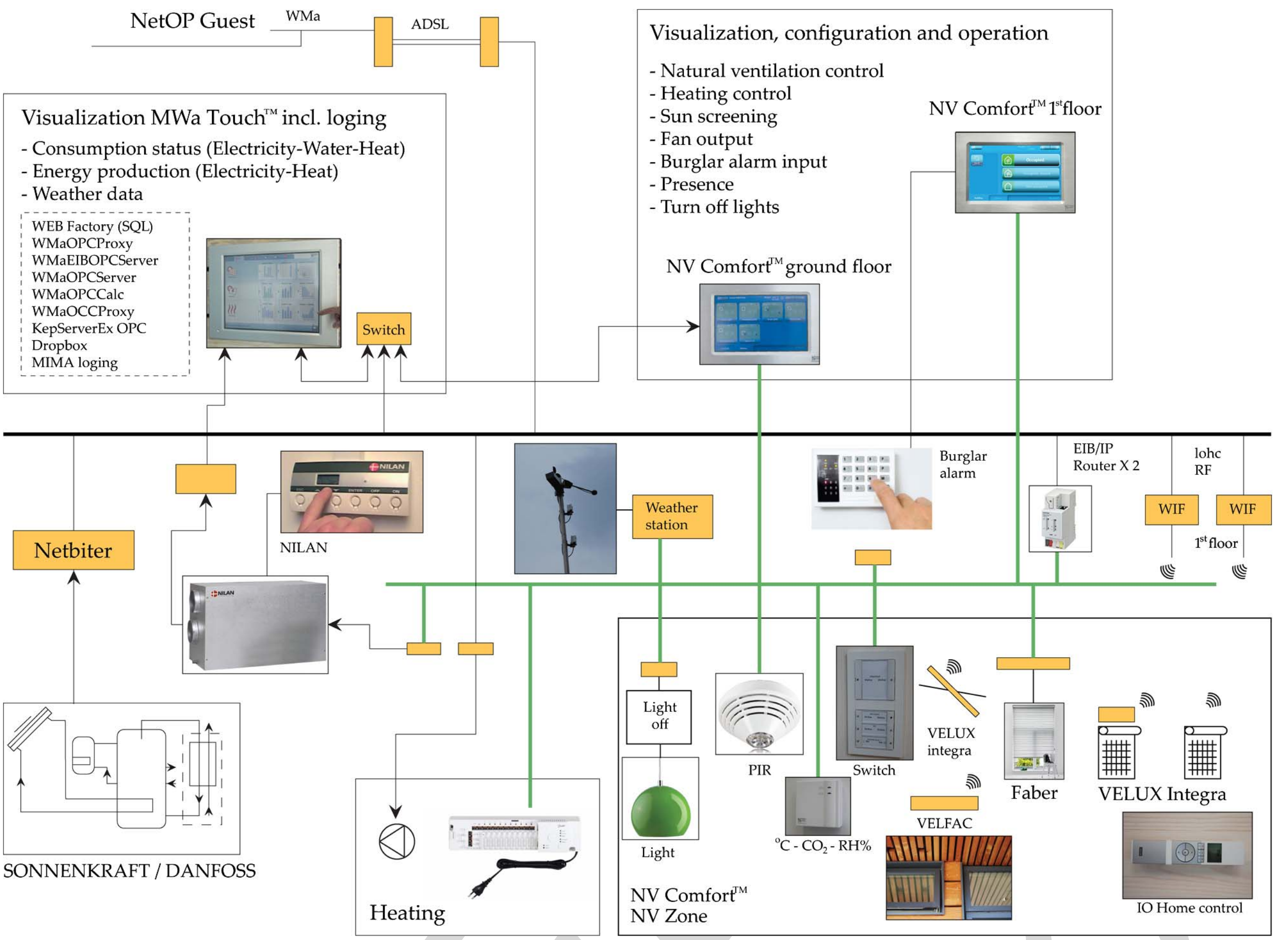


**Fig. 3.** ***System description of the house. By WindowMaster.***

and 3-D animations in Velux Daylight Visualizer2. Estimated energy consumption and production as well as indoor climate values were continuously calculated in the Danish software programs BSim and Be06. These calculations were used at all interdisciplinary workshops to identify relationships between technical elements and aesthetic considerations in all design strategies, in order to be able to communicate across disciplinary boundaries with a common language and set of concepts. By looking at the smart window as a holistic design element, we became aware of the fact that the usually employed, quantitative energy performance criteria were in conflict with other qualities of window design.

The process resulted in a design that unites low-tech and smart high-tech elements through an intelligent control system with sensors in all rooms registering temperature, $CO_2$, and humidity; and a weather station on the roof registering wind speed and direction, temperature, and rain. Both are connected to the mechanical ventilation with heat recovery, the heating system, and not least the smart windows; see the system description in Fig. 3.

The energy is produced by technologies integrated in the building, harvesting the energy directly from the sun and converting it into electricity and heat. The 50 m$^2$ of polycrystalline photovoltaic panels with 13% efficiency generate about 5500 kWh a year. That is 20% more electricity than the house is expected to need, although in winter, it does draw some power from the electricity grid. The frameless dark photovoltaic panels are carefully integrated into the dark slated south-facing roof as part of the roofing [7].

Heating comes in through the windows supplied by the solar thermal collectors. 6.7 m$^2$ of collectors catch the sun's rays on copper plates integrated on the lowest part of the south sloping roof between the roof top windows. Underneath the plates, copper pipes circulate fluid that absorbs the heat of the plates, converting 95% of the sun's energy into heat. The collectors can catch indirect sunlight, as well, so the house still has heat on cloudy days. Should more interior heating be needed, an air-source heat pump will be activated. In one common configuration of this type of pump, air passes through a heat exchanger placed outside the house to transfer the air's warmth to a liquid medium. The liquid travels to an electricity powered compressor inside the house, which applies pressure to raise the fluid's temperature further. In general, a heat pump is far more energy efficient than conventional oil or electric heating, and it has lower $CO_2$ emissions. The pump's performance depends heavily on the amount of heat contained in the air; when it is cold outside, these heat pumps are not efficient. To avoid that problem, the heat pump uses the solar collectors to preheat the cold winter air before it reaches the heat pump. The pump can then easily produce 20 °C water even when the outside air is below freezing. After the liquid is compressed, the heat travels through pipes in the floor and radiators. In all, the solar collectors and pump are calculated to produce 8000-kWh heat a year [7].

The house is designed to use the daylight as en energy optimizing and architectural design parameter to let heat, fresh air, and light into the interior and to produce energy directly from the sun. The house does not need a cooling system, because it provides both ventilation and screening of the sun when needed. This is where smart windows come in. The Home for Life has about double the window area of an ordinary Danish single-family house. This is possible because of the specialized energy optimized panes with two or three layers of glazing, depending on orientation, which in the cooler months reduce the heat escaping from the inside while allowing ample heat and daylight to enter. In fact, the windows alone are estimated to deliver half of the heating needed during wintertime.

Windows in all four walls and a slanted skylight flood the rooms with sunshine. Built-in external blinds move autonomously to adjust to glare and heat, angling slats in response to climatic conditions. To bring in more fresh air, the horizontal top windows and skylights slide open with a hiss. "*It's fun to listen to*" the children report [10]. To minimize the need for artificial lighting, we designed the space so that daylight pours in from all four directions. These are clearly articulated in the plan through a "cross of light" shown in Fig. 4, which also defines exits, ventilation openings, seating recesses, and frames around views.

The large windows cut down on the amount of electrical lighting and mechanical ventilation needed. A roof overhang on the south side provides shade when the sun is high in the summer, and shutters and blinds on both sides of each window regulate the transmittance of heat and provide privacy; see illustration of the many regulating layers in the smart window in Fig. 5.

To further reduce the risk of overheating, the windows are programmed to open on their own to let in fresh air. Sensors in every room track the temperature, carbon dioxide levels, and humidity, and a weather station on the roof monitors outside conditions, including temperature, wind speed, rain, luminance, and solar radiation. All information registered by the sensors is gathered by the intelligent control system.

The control system uses that information to decide when to lower the solar screens or slide open selected panes or both. These automated adjustments of the windows, rather than traditional air-conditioning and heating, provide the bulk of the house's temperature control.

### B. The Actual Energy Use and Indoor Climate

Three main data sets were collected: quantitative technical performance measures; qualitative data on occupants' experiences; and observations on the experience windows give to the house and its spaces, captured through photography and daylight modeling.

The house has been inhabited by two families. Family 1 (F1), a mother, a father, and three children ages 0, 4, and 7, have lived in the house for a year. Most of the registrations from this family are from anthropological studies from the research project Minimum Configuration, Home Automation [9], [10]. Afterwards, family 2 (F2), comprising a male and a female and sometimes their grown up children, bought the house. The registrations for this family are from a journal they have kept for researchers [1]. The qualitative registration has been through participant observations [10] (see anthropologist and occupant in Fig. 6), cultural probes such as monthly diaries and photos, as well as observations by the architects [1], [8], [10]. Methods for quantitative registration include energy simulation with solar heat gain and losses in BE06 and Bsim, simulation of indoor climate conditions, simulation of natural ventilation, simulation of daylight, measurements of daylight, and luminance mapping [9], [12]. Some of the preliminary findings are that the energy consumption for heating was higher than expected, primarily caused by different forms of user behavior than anticipated. The calculated requirements for heating were 15 kWh/m$^2$/year, and the normalized requirements of the actual use are 20 kWh/m$^2$/year after two years of occupation. According to Velux [6], 62% of the divergence from the calculated and actual use is caused by a different user behavior than expected, such as higher room temperature, manual override of sun screening, higher need for domestic hot water, and lower internal heat loads (appliances + persons). Another factor is the building itself, which gave a 19% performance deviation due, among other things, to a less than anticipated sealing of the envelope. Finally, the technology control systems cause a further 19% of the divergence due to dissimilar performance than expected by the heat pump, technical regulations of solar screening, and efficacy of heat recovery.

It was also found that a good indoor climate requires sun screening and effective control of the hybrid ventilation system. To achieve the optimum indoor climate, it is important that there are openable windows in every room. According to Velux [6], the kitchen/dining room which has a large south-facing window area and, consequently, a huge influx of daylight achieves category 1 in terms of

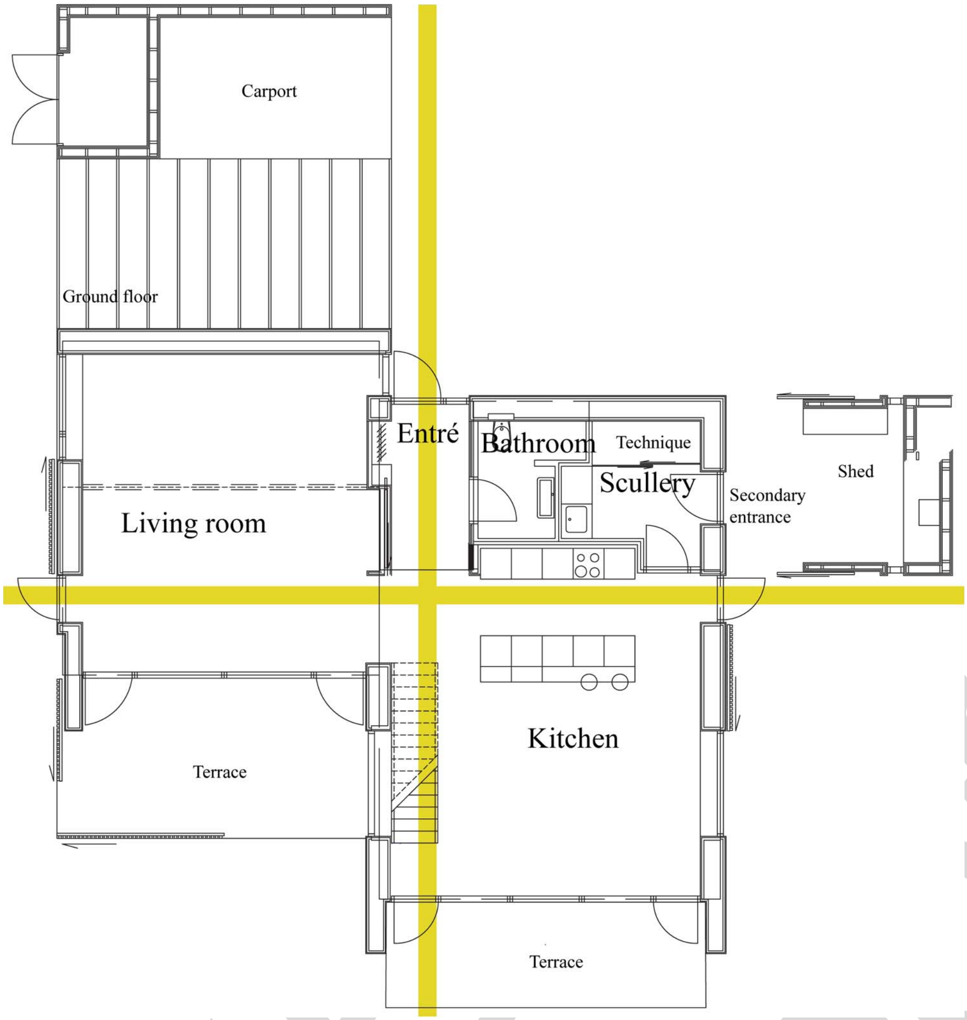


**Fig. 4.** ***Plan drawing of the ground floor illustrating the entrance from the north, the living room facing south-west and the central kitchen dining room facing south. The yellow "light cross" illustrates the light openings in all four directions.***

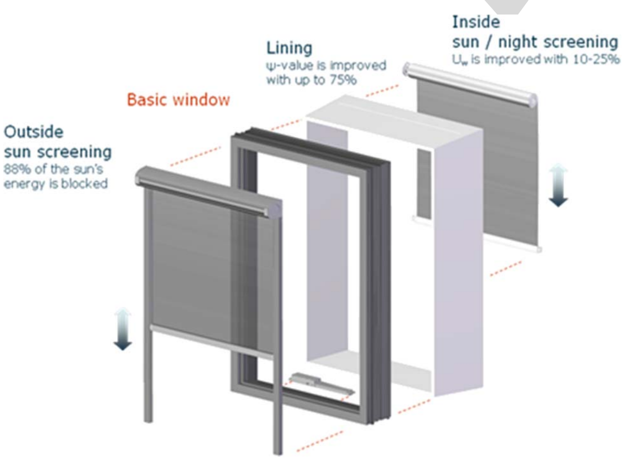


**Fig. 5.** ***Smart window construction illustrating the many regulating layers in a smart window. By Velfac.***

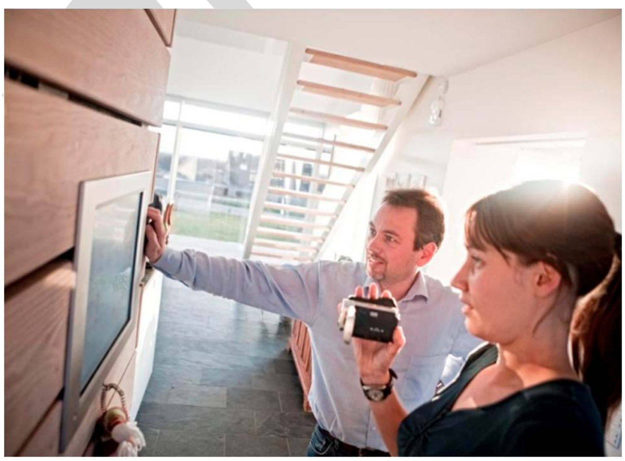

**Fig. 6.** ***The anthropologist's exploration of the house where she explores the occupants and their views on living in a smart home.***

Table 1 The Four Window Design Elements: the South-Facing Smart Window; the Square East/West-Facing Windows; the North-Facing Rooftop Windows; and the Light Cross

| Design element | Images | Description |
| --- | --- | --- |
| South facing active facade |   | - Constitute all south facing façades of the kitchen, the living room and the south facing room on the first floor.<br>- Vertical fixed windows and doors, over which are installed a number of horizontal windows for automatic natural ventilation.<br>- External automatic sunscreen and internal roller blinds adjust the heat gain and light. |
| East and west facing windows |   | - The three windows are placed parallel to each other in the kitchen and in the living room in the north-west corner.<br>- The windows are fixed parts with no pane sections.<br>- Internal roller blinds and external manually operable shutters adjusts light inlet. |
| North facing roof windows |   | - Two bedrooms and the bathroom on the first floor are supported with light from six north facing roof windows.<br>- The pivot windows have automatic window operators, external awning blinds, and internal blackout blinds. |
| Light cross |     | - Four doors giving view and access to the north, south, east and west are visually connected in a cross at ground level.<br>- The concept is repeated on the first floor with openings facing east and west.<br>- The door facing north serves as main entrance. A ventilation window is placed over each of the three remaining doors. |

thermal comfort and overheating. This is the best of four classes of the European standard EN 15251 for indoor climate. This fact emerges from the measurement results, which show that the room is in category 1 96% of the time in terms of thermal comfort. The balance between automatic control and the opportunity for resident control can be optimized, partly in terms of hybrid ventilation systems, the use of external sun screening and user interaction, so that the house creates a greater possible degree of comfort with the lowest possible use of energy. Control in the spring and autumn in particular can be optimized. Considering this categorization, it is interesting that the qualitative interviews showed that the occupants in many cases deactivated the solar shading in favor of daylight, views, and contact with the surroundings [1], [8], [10]. Some overheating has been recorded, which to some extent was caused by the occupants overriding the solar shading. The occupants have also overridden the system by manually opening the windows in the heating season for fresh air, which influences the energy consumption for heating [9].

This underlines the necessity of awareness of a more hybrid understanding of how the technical and energy-efficient approach is influenced by the experience of living in the house. It also illuminates the smart window as a central design element, not as a component but as a multidimensional design element, where context, technical, and aesthetic parameters are considered. To explore this, we have categorized the windows in the Home for Life as four window design elements. In Table 1, the four window design elements are illustrated: the south-facing smart window; the square east/west-facing windows; the north-facing rooftop windows, and the light cross [2].

## III. THE SMART WINDOW: A MULTIDIMENSIONAL DESIGN ELEMENT?

In the following, we explore how the smart window as a central design element needs to be defined through a broad multidisciplinary approach—a multidimensional design process. We want to illustrate that the hybrid approach can be used both as an aesthetic device and a technical tool to improve quality of life in energy positive homes.

The total window area in the Home for Life is 70 m$^2$, corresponding to 40% of the floor area, about twice the area of windows in traditional Danish houses. The window area of the four façades is distributed as follows: 70% south, 5% north, 11.5% east, and 11.5% west [2]. During the heating season, automatic natural ventilation from the window openings is supplied by mechanical ventilation, through the means of heat recovery. The Danish energy frame simulation program BE06 estimates that 50% of the energy needed for heating is covered through passive heating through the windows [6].

### A. Analyzing the Window Through Aesthetic and Technical Means

There is an increasing tendency in newer buildings to orientate windows so that they may optimize the gain of solar heat. This tendency is a result of quantitatively defined criteria for the reduction of the energy used on heating. However, windows are also essential for the quality of life; they affect our senses and perception of surrounding environments to a great extent as has, for example, been shown in a large number of studies in hospital environments [11]. Thus, focus on the possibilities of harvesting energy directly from sunlight should be combined with the unique opportunities for designing buildings with the best possible natural environments for people; design and new technologies integrated into smart windows require that aesthetics, user experiences, and technical aspects of daylight are addressed [13].

Instead of looking at the performance of the window as an isolated building component, we have already defined four window design elements (Table 1) used in the design of the Home for Life. Analyzing the window design elements in this way makes it possible to look at the performance of the smart window where the context of orientation, function, and indoor and outdoor relations differ.

The following analysis focuses on finding technical and aesthetic aspects of the window design elements in the case study house, where smart windows are key design components to improve indoor climate and the quality of living in the house. The intention of this analysis is to articulate design parameters, which contribute significantly to the smart energy-optimized house [2], such as:

1) expression of space and materials evoked through daylight;
2) indoor and outdoor relations;
3) functional daylight conditions;
4) fresh air and comfortable temperature;
5) solar heat gain.

*1) Expression of Space and Materials:* The kitchen/dining space is the central and most expressive room in the house as all of the four window design elements are represented in this space. In the kitchen/dining space, the light comes in from five directions. There is constantly sunlight in the kitchen/dining space throughout the year from sunrise until sunset. The entering sunlight adds varying and dynamic accentuations of the space, made more expressive by the automatic external and internal blinds. Fig. 7 illustrates the kitchen/dining room and the changes of light in June in response to the active façade and at noon and in the evening. The first picture illustrates how the sunlight from the rooftop windows strikes the wall and how the sunlight from the south-facing glass façade is blocked by the eaves to prevent overheating from the sun during summer. The second picture illustrates the same daylight situation, while the external shading is down on

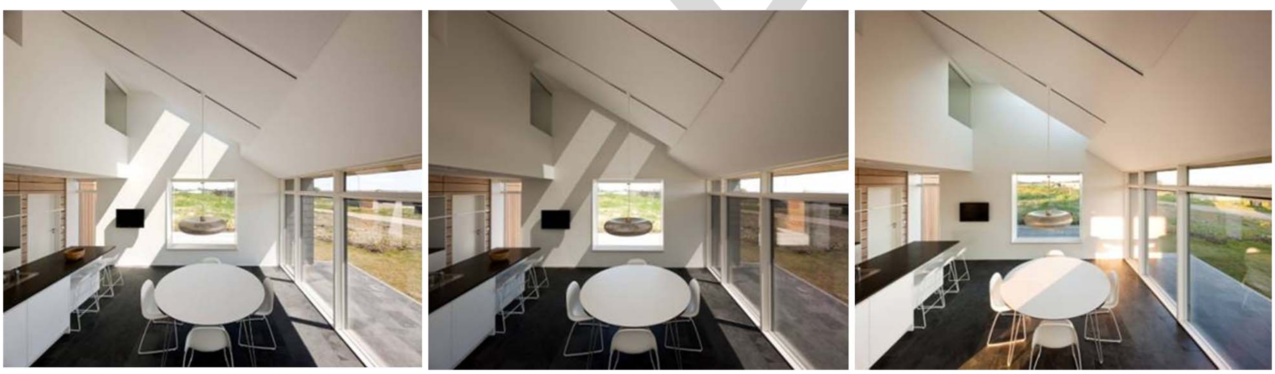

**Fig. 7.** ***The kitchen/dining room looking east. The light and atmosphere in the room change according to the smart façade and the time of the day. Photos by Adam Mørk.***

the south-facing façade and on the roof top windows to prevent overheating. It creates another atmosphere in the room because of the indirectly filtered light through the blinds, reducing contrasts and glare. The third picture illustrates the warm low evening sun lighting up the space from west–north–west.

The room is characterized by a sloping ceiling, which is a result of the south-facing roof being generously extended to optimize for the generation of energy. Internal windows to the middle bedroom and toilet plus the south-facing bedroom strengthen this effect. The skylight penetrates through the north-facing roof window in this south-facing room.

The modernistic motif of the south-facing glass façade creates a contrast to the east/west-facing windows, which appear as classic holes punched into the façade, through which the hot and low sunlight is transmitted in the morning and evening hours. The thick, well-insulated walls and the insulating qualities of the glass create a space for a window recess with a place to sit. In her diary in March 2011, the female occupant of the house, family 2, F2F, writes:

> "The window sill in the east-facing window is quite naturally used as a seat several times a day. It is a good place to get lost in one's own thoughts with a cup of tea after work, or a good place for a break" [1].

After the first three months, test family 1 (F1) explains:

> "The best with this new house compared with our old house is the light. The light is better and, look, we are sitting here, it is past 7 P.M., and the light over the dining table is not lit" [8].

In May 2011, F2F writes in her diary:

> "We still notice the many beautiful details of the house, including both the slated façades and the changing light in the house" [1].

The occupants enjoy the daylight from all directions, which is possible because of the smart window system.

*2) Indoor and Outdoor Relations:* The two east/west-facing windows and the south-facing active glass façade create a strong transparent connection to the outside, illustrated in Fig. 7. The "light cross" also contributes to opening up of the house, connecting to the west through the living room and to the north through the hall. In the participant observation, the anthropologist writes:

> "Sitting in the kitchen/family room you easily let your eyes wander to follow life outside the house. The six-year old boy of the family tells how the family from the dining table can watch the sun rise and the mother of the family fancies looking out of the windows and compares the windows to pictures. One window represents one picture; another window is a new picture, etc. And they are always different. Actually, they enjoy the view so much that they like to let in more light and heat than permitted by the smart system. Then, they override the system and roll up the awning blinds when the system tries to control the heat" [10].

The south-facing window façade faces the road in front of the house, resulting in the occupants pulling down the sunscreen to have more privacy [12]. This interferes with the expected amount of energy gained through the façade. The anthropologist points out:

> "At the beginning, the family asked for blinds on the first floor, in the living room, and in the kitchen/family room. They are used a lot, and at the same time, the family is excited about the great view from the house, which is considered a great asset to the house. So, in general, there is a conflict between the need for screening as a means of controlling the temperature on the one hand, and the view and the daylight admittance on the other hand" [10].

In May 2011, the female occupant of the house F2F writes in her diary:

> "We still notice the many beautiful details of the house, including both the slated façades and the changing light in the house. We do not have to get up from the chair and walk to the window to look out. The big windows provide a view, whether we are cooking, sitting in the living room or in our rooms" [1].

It has also been reported that the families, in some cases, pull up the sunscreen to get the view, which can cause overheating [10].

The occupants like the connection to the outdoors; sometimes they need screening for privacy and sometimes they pull up the screen to get the view. These needs can conflict with the need for regulating the façade for passive solar heat and overheating. The occupants end up overriding the intelligent system to fulfill their needs for view and privacy.

*3) Functional Daylight Conditions:* The two large square windows facing east and west, the south-facing active window façade, and roof windows in each side of the south-facing roof slope result in a daylight factor average in the kitchen/dining room of around 10%, with large areas of the space exceeding daylight factors of 20% [12].

Glare might occur. F1 pulled down the internal and external blinds to dim the light level and create privacy, which has resulted in reduction of possible solar heat

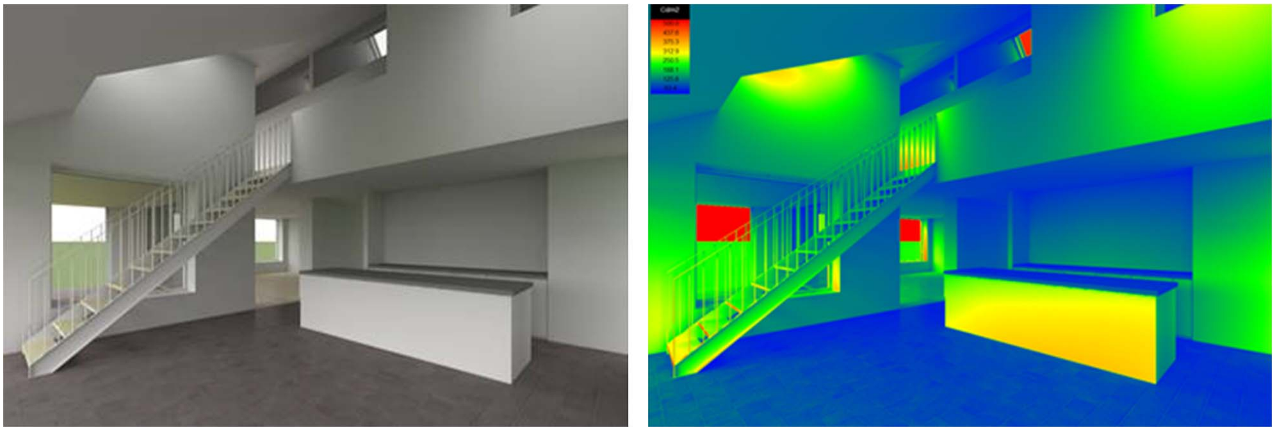

**Fig. 8.** ***The kitchen/dining room looking west. Two simulations show that the space has a very well-distributed daylight environment. Simulations developed in Velux Daylight Visualizer 2.***

gains. The south-facing active façade is critical in the southwest-facing room on the first floor. F2F writes:

> "It is nice to have so much light in the house. The character of the light changes with the weather. However, my husband has to pull down the external sunscreen to the balcony in the office during the day. The internal blinds are not enough. Too much reflection in the computer screens makes work impossible."

She adds:

> "Evening blinds and sun screening have started to go down later, meaning that we can enjoy the days getting longer. The timing is perfect."

This accentuates the experience of the house following the rhythm of day and year [1]. See photo and daylight simulations of the kitchen/dining room looking west in Fig. 8 and daylight simulations showing the daylight factor (percent of daylight in the room) of the ground floor and the first floor in Fig. 9.

F1 experienced using very little electrical light due to the level of daylight, and the anthropologist notices:

> "The family has the experience that they use less electrical light than in their old house and they mention the great amount of daylight intake as one of the things they will miss the most, when they move back to their old house from the 1970s" [10].



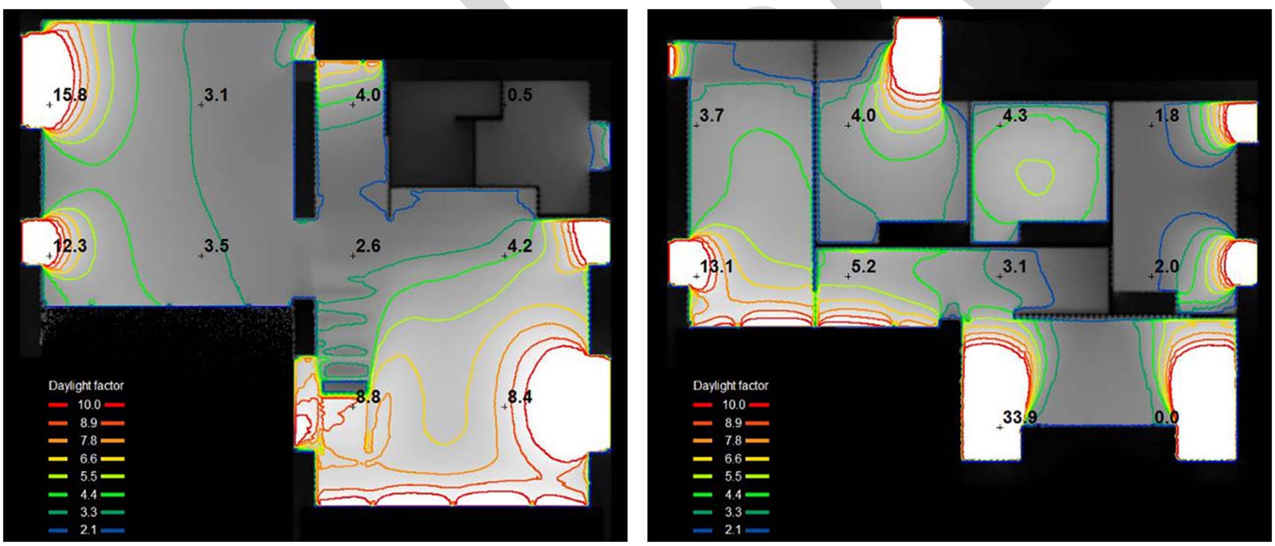


**Fig. 9.** ***Daylight factor at ground and first floors. Simulations developed in Velux Daylight Visualizer 2.***

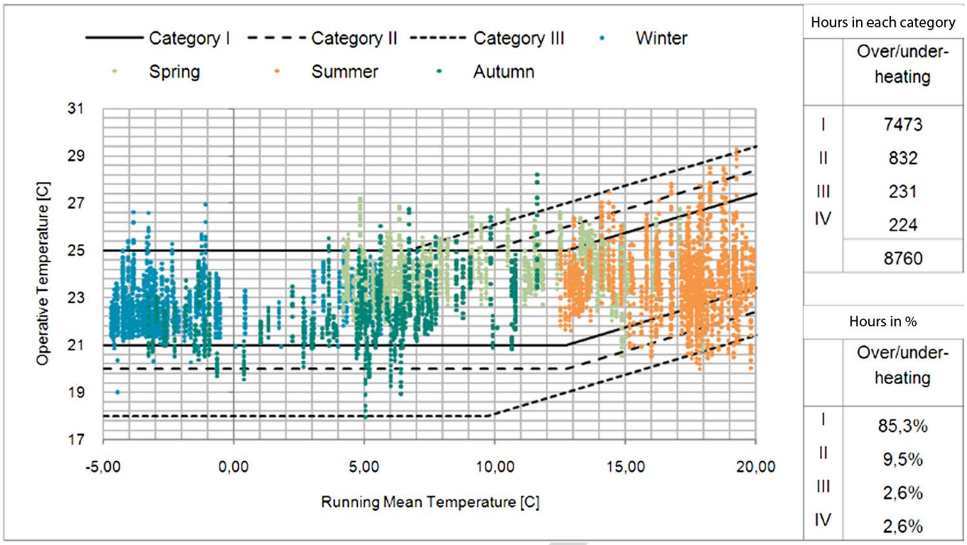


**Fig. 10.** ***Indoor climate illustrated according to the European Standard EN15251 showing the measured operated temperature as a function of running mean outdoor temperature. The columns to the right display the number of hours of over/underheating in relation to the categorization in EN15251.***

The high daylight level reduces the use of electrical lighting. Internal and external shadings are manually used to avoid glare; this can conflict with the need for passive solar heating, which is primarily needed during the heating season, where the sun is low and, therefore, increases the risk of glare.

4) *Fresh Air and Comfortable Temperature:* The top windows in the south-facing façade and the doors placed on the "light cross," together with the roof windows, are programmed for automatic natural ventilation. This aspect of the design has been carefully cultivated. In March, F2F writes:

> "In March, we experienced that the house changed from winter to summer. The first time the house went into summer state it took us by surprise. It acted differently than we were used to. The windows and roller and awning blinds went down. The air felt and smelled fresher—real outdoor air" [1].

The south-facing windows are supported with external automatic sun screening and internal blinds. Temperature was measured to be below the criteria of category 1 in EN15251 for more than 96% of the year. However, the measurements and the observations indicate that there are periods, especially during spring and fall, and shorter periods during summer, when overheating occurs [9], [10]. In Fig. 10, the measured temperatures in the house are shown for the first year in relation to the measured outdoor temperatures illustrated according to the European Standard EN15251. The horizontal axis displays running mean temperature in degrees Celsius (outdoor temperature), while the vertical axis displays the measured operative indoor air temperature in degrees Celsius. The colored dots are all individual hourly measurement points of indoor air temperature; these are colored in relation to the season in which they are measured, respectively, winter, spring, summer, and autumn. For example, the blue dots are indoor air temperatures measured in winter time and are related to the colder outdoor temperatures, whereas the opposite applies for the orange summer measurements. The three types of lines across the table represent categories I, II, and III, defined by the European Standard EN15251; thus, the amount (or percentage) of hours that fall between these lines determines the category of the temperature conditions of the house. The tables to the right of the graph display how many hours fall within each category. The column "over/underheating" shows the number of hours that fall within the area of the respective categories; 7473 h fall within category I and then additional 832 h fall within category II, and so forth. Fig. 10 describes the percentage of the number of hours that fall within each category; 85.3% of hours fall in category I, equaling 7473 h of the total 8760 h in a year. Ideally, all temperatures should be within category I.

F2 experienced overheating primarily during winter, which was clearly stated in the diary by F2F from December:

> "A Sunday with plenty of sun and more than 27 °C in the living room. We had to have the automatic control ventilate a couple of times, but we felt more like opening all doors to outside, to the 2 °C below the freezing point. We did not, but we sat for a while on

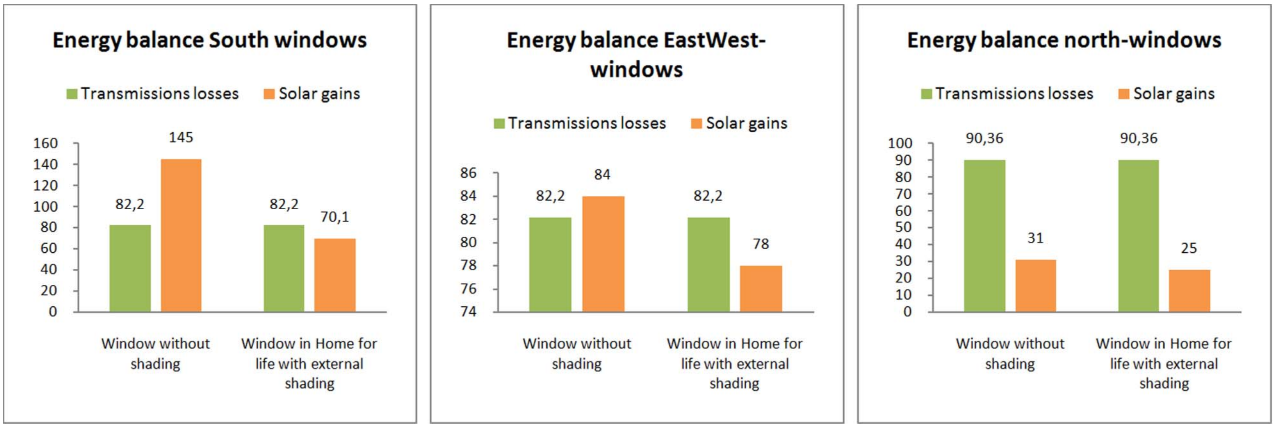


**Fig. 11.** ***Energy balance, the solar gain, and transmissions losses in all four directions.***

the terrace by the living room. The house keeps the warmth, which we could benefit from later that evening and that night. It is still winter, you know" [1].

A couple of months later, in February, F2F continued:

"We had the pleasure of the sun in February. We came home late on a Saturday afternoon. It was probably 29 °C in the living room and 27 °C in the kitchen. When we entered the house, we were cold, so feeling the warmth was actually very pleasant. The sun was also strong the following day. We pulled down the awning blinds in the kitchen, which instantaneously gave us a pleasant feeling, and the temperature stayed at an acceptable level around 24 °C–25 °C" [1].

Finally, in May, F2F writes:

"When we experienced in January how the low sun could heat the house up to 28 °C–29 °C by frosty weather, we feared the extensive heat in the summer half-year. However, we managed to keep pleasant temperature. On hot days, the house feels cooler than the temperature outside. It does not take much sun to activate the sun screening and ventilation. Usually, the house is prepared to provide heating, and the air in the house is always fresh" [1].

Automatic natural ventilation and automatic external shading are important elements to prevent overheating and support the house with fresh air. During winter, when the sun is low, it is not always possible to prevent overheating by shading and mechanical ventilation. To save energy on heating, the system is not programmed to cool through natural ventilation during the heating season.

*5) Solar Heat Gain:* According to calculations, the south-facing window supports the house with solar heat during the heating season, the east/west-facing windows are neutral, and the north-facing windows bring no energy [7]. During the design of the house, it was simulated that half the required energy needed for heating could be covered by solar heat gain through the windows [7]. See Fig. 11 for energy balance, the solar gain, and transmission losses in all four directions. The figure shows the so-called energy balance of, respectively, the south-, east/west-, and north-facing windows. Each diagram has two sets of columns; the first shows the window without shading and the second shows the window with external sun shading. The green, left column shows the transmission loss: the calculated loss of energy from the house to the outside through the window. The orange, right column shows the calculated heat gain from the sun that enters from the outside through the window. In case of the south-facing windows with no external sun shading, more heat enters into the building than is lost and the window supplies the building with energy in the form of heating. When external sun shading was added to south-facing windows, only half the solar gains were supplied to the building, compared to previously resulting in a transmission loss, which is a little larger than the solar heat gain. Here, it is also important to consider the consequences of heat loss (or gain) through the window in terms of overheating inside the house or the fact that sun screening may limit the views of the outside. The diagram also shows that the south façade has the largest possibility for supplying the building with heating, whereas the north-facing windows have the smallest potential; east/west-facing windows have the potential to gain as much energy as they lose, which is the ideal scenario.

F2 shows interest in the fact that the sun supports the house with energy. In November, F2F writes:

"We hope for a very sunny winter to support the balance of energy. 'Good weather' has a completely new meaning to us now" [1].

Table 2 The Table Presents Negative and Positive Impact Aspects of the Respective Window Design Elements. The Table Presents the Contradictions in the Different Values and Thereby the Importance of Defining the Window as a Multidimensional Design Element in the Design of Smart Homes

| | | South facing active facade | East and west facing windows | North facing roof windows | Light cross |
|---|---|---|---|---|---|
| AESTHETIC | Expression of space and material | + | + + | + + | + |
| | Indoor and outdoor relations | + + | + + | + | + |
| | | **Both yes and no** Yes: Openness underlines indoor/outdoor relation and good daylight conditions. No: The transparency displays the occupants and limits privacy. | **Yes** Yes: Variation of light intake creates possibilities in spatial experiences changing over day and year, casting light deeply into the space; the sills provide built-in furniture. | **Yes** Yes: Diffuse daylight contribute to experiential qualities of space and provide a good even daylight environment. | **Yes** Yes: Transparency creates a feeling of safety for the occupants and the doors provide direct access to the surrounding in all directions. |
| TECHNICAL | Functional daylight conditions | + | + | + + | + |
| | Fresh air<br>Comfortable temperature | +<br>- | + / -<br>- | + +<br>+ + | +<br>+ / - |
| | Solar heat gain | + | + / - | - | + / - |
| | | **Both yes and no** Yes: Passive energy from solar heat gain. No: Too much solar heat gain creates overheating, sunscreen and natural ventilation required. | **Both yes and no** Yes: Provides daylight deep into the spaces morning and evening No: The low solar inlet during spring and fall result in overheating. | **No** No: No passive energy contribution through the window but energy loss. | **Yes** Yes: Possibility of cross ventilation, intake of air for natural ventilation and letting daylight deeply into the spaces throughout the entire year. |

The south-facing windows support the house in the heating season, but not as much as was calculated, which was mainly caused by a different user behavior than predicted in the simulations.

## IV. DISCUSSION

With the aim of illustrating how a multidimensional approach to the smart window as a design element can be used both as an aesthetic method and a technical tool, this paper focuses on a key subject within the ongoing sustainability discourse: how can smart architecture improve quality of life and not merely technological prowess? The case study used presents an experimental, full-scale, energy-positive house with real occupants and professionals involved. While the presented data are drawn from the large amount of information gathered, much larger than can be presented in this single paper, important evidence indicates that the window is of primary importance as an element of the "smart house."

There are obvious technical disadvantages to designing energy-positive houses with extensive glazed areas. Healthy indoor climate conditions are defined by standards such as the European Standard EN15251 or energy performance defined in the Passive House Standard. However, the occupants' experiences in the present case study point to the importance of their experience of smart windows and the subsequent effect of their experiences on energy use. Differentiated daylight, awareness of architectural space, fresh air, glare, relation to site-specific surroundings through physical and visual access, and views of the surrounding landscape and cityscape are all essential factors to be considered in future sustainable housing, which aims to have life-improving effects. In Table 2, we have rated the window design elements in relation to the aesthetic and technical findings described in this paper. (−) indicates that the window design element does not add to the quality of living, whereas (+) or (+ +) indicates that the window design element adds "good" or "very good" qualities to the house [2].

The analyses also underline various contradictions between aesthetic and technical aspects, which illustrate that it is imperative that potential conflicts be addressed as early as possible in the design process. The issues about quality are important but are often overlooked in a purely technical analysis. An occupant-oriented approach to both programming and analysis of the houses is valuable for an optimal use of daylight potential. Focus on the life in the house and the potentials of smart solutions help us in understanding how to work with nature instead of fighting it. It also helps us understand how new products and technology can meet traditional and future requirements.

We maintain that there are potentials in a multidimensional approach to the design of smart energy-optimized homes. All four analyzed window design elements afford occupants with aesthetic qualities, such as the evoking of space and materials through daylight, indoor and outdoor relations. While it is clear that the aesthetic aspects of dwelling in a smart house have an important role to play in its design, this paper points out that these aspects do not always correspond with the technical demands placed on the design. The challenge is to develop tools, design strategies, legislation, and building components where the complex synergy between technical and aesthetic design parameters can be united in smart homes—smart homes for people. ■

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