Influence of Occupant Behavior and Operation on Performance of a Residential Zero Emission Building in Norway

Authors: Natasa Nord[1*], Tymofii Tereshchenko[1], Live Holmedal Qvistgaard[2], Ivar S. Tryggestad[3]

Affiliations:

[1]Norwegian University of Science and Technology, Department of Energy and Process Engineering, NO-7491 Trondheim, Norway

[2]Norconsult AS, Norway

[3]Cowi, Norway

[*]E-mail address: natasa.nord@ntnu.no. Phone number: (+47) 73593338.

Abstract

It has been proven that occupant behavior may significantly change building energy performance. The effect of the occupant behavior is becoming even bigger when it comes to highly energy efficient buildings. Specifically Zero Emission Buildings (ZEB) may become an issue for the electric grid, because they are supposed to be actively connected to the electricity grid for electricity import and export. Therefore, the aim of this study was to evaluate the change in the energy performance of a ZEB located in Norway. Occupant behavior was modelled by using the following methods: standard schedules, well-defined profiles based on thorough statistical analysis, and stochastic methods. To analyze the grid stress, 31 scenarios for different occupant behaviors were analyzed. The overall estimation of investigated parameters showed that the change in occupant behavior resulted in grid stress variance from -5% – +13% compared to the reference case based on the standard values. The results showed that the occupant behavior might change the annual energy balance reliability by 20 %. However, the results showed that the influence of the occupant behavior related to the window opening and domestic hot tap water would not significantly change the ZEB energy performance. Window opening would even decrease the cooling load. A very important conclusion of this study is that consideration of

occupant behavior through challenging the standard values are highly necessary for reliable energy analysis of the ZEB solutions.

Keywords: zero emission building; residential buildings; occupant behavior; electric grid interaction

Nomenclature:

$Pow_{mis,i}(kW)$	power mismatch at the ith hour
$Pow_{con,tot,i}(kW)$	total hourly-average building power use at the ith hour
$Pow_{PV,tot,i}(kW)$	total hourly-average PV power generation at the ith hour
$S(-)$	grid stress
$STD(-)$	standard deviation
$\varphi_j(-)$	annual energy balance reliability at the jth year

1. Introduction

The annual energy demand in the building sector in Norway corresponds to 40% of the total national energy use, of which 22% goes to the residential sector and 18% to the non-residential sector [1]. In residential buildings, space heating and domestic hot water (DHW) production constitute approximately 70% of the total energy use [2]. The building sector presents a great potential for nationwide energy savings. Predictions indicate that the Norwegian energy use for residential purposes will be reduced by 75% in 40 years from now. In 2010, the European Union adopted a recast of the Energy Performance of Buildings Directive (EPBD). It states that all new buildings in the EU will have to be ‘nearly zero energy’ by 2020 and that the energy will be ‘to a very large extent’ from renewable sources [3].

Zero Energy/Emission Building (ZEB) has become a term for buildings that are self-energy supplied or may even export energy. These buildings are characterized by energy efficient components and energy supply from renewable energy sources [4]. A building may be characterized as a ZEB when it is able to export excess energy generated by renewable sources, for instance by photovoltaic (PV) modules, to the grid and achieve an annual positive net balance between demand and supply. Different ambition levels within the ZEB definitions have been suggested depending on the different emission items included in the calculation [5]. The starting point in a ZEB design is to start from a passive house requirements for building envelope or currently valid national building code. Residential passive buildings are characterized by energy-efficient building envelope. Requirements for specific heating energy use and specific heat rate in dwellings of the passive house standard is 15 kWh/m^2 and 10 W/m^2 [6]. However, achieving these requirements is complicated in Norway due to a colder climate compared to Germany, where the passive house standard was first introduced. In Norway, these requirements are stated in the standard that describes necessary prerequisites for passive houses and low energy buildings [7]. As a result of low space heating demand, the DHW heating demand presents an increasing share of the total heating demand that correspond to 40-85% in residential passive buildings [6]. This gives the DHW preparation a greater role in modern buildings than before.

Stricter regulations for the energy use in buildings mean that the buildings constructed these days are expected to be significantly more energy efficient. However, the measured performance of modern low-energy buildings is often below expectations. Occupant behavior has been found accountable for variances in excess of 50% in use of electrical equipment between design and measurements, and even larger variances when it comes to DHW use. Ventilation rate and indoor air temperature are also found to vary greatly in actual use compared to the desired or set values [8-10]. Simulations of indoor environment and energy use are becoming increasingly important in the design phase of buildings. However, the discrepancies between simulation results and actual energy use may be very big and may be induced by different factors. This difference has become known as the “performance gap” [11]. One of the most important conclusions from the International Energy Agency (IEA) Annex 53 - Total Energy Use in Buildings: Analysis and Evaluation Methods is that the occupant behavior is one of the reasons inducing a significant difference between the simulated and real building energy use [12]. Creating simulation models that are able to simulate user behavior accurately has been proven to be difficult, and standardized patterns for use and internal gains are often used [13]. Different methods have been used to model occupant behavior to evaluate influence of the occupant behavior on the building energy use, such as simplified schedules, well defined profiles, and stochastic methods [14]. In the case when it is very complicated to use data-mining techniques to analyze occupant behavior and integrate this into the building simulation programs, use of well-defined user profiles showing standard deviation of the values may be very successful [15]. Since ZEB is connected to the electricity grid, big variations in the estimated electricity use will also influence the electricity grid. For example, it was show that a ZEB located in Norway may perform as a normal building – using electricity from the grid in winter, while in in summer the same building may produce much more electricity than its need [16]. Therefore, the aim of this study was to show change in the ZEB performance caused by the occupant behavior. Due to different occupant behavior both indoor environment and energy performance of the ZEB may be changed. Due to importance of proving the ZEB performance during the building life-time, it was highly important to integrate a complex simulation model of a ZEB and detail occupancy models. In this study both well-developed schedules and stochastic models for the occupant behavior were implemented for the occupant behavior model. That way, it was possible to analyze and understand the change in the ZEB performance caused by the occupant behavior.

Since the actual energy use has been shown to deviate a lot from the requirements due to different reasons, this study aimed to analyze the impact of user behavior and building operation on the ZEB residential house under Norwegian conditions. This study differs among other literature, because it included detail occupant behavior models that have been validated and are found in literature. The detail occupant behavior models included the following: DHW use, light use, window opening, and electric appliance models. This study attempted to show change in the indoor environment and ZEB energy performance caused by occupant behavior.

The paper is organized as the following. First all the introduced occupant behavior models are presented. The case study ZEB demo house is introduced afterwards. Finally, the results showing achieved indoor air quality and energy performance considering different occupant behavior are presented. A summary of electricity grid interaction indices was also made and is presented at the end of the analysis. For a ZEB building, it was found that showing only annual performance data was not enough. Therefore, in this study a detail analysis on hourly level of the electricity grid interaction indices was made.

2. Methodology

Relevant information about the ZEB dwelling was collected from the project owners. Based on this, a reference model of the SFD and its energy supply system was developed using the dynamic simulation tool IDA ICE 4.7 [17]. The performance of the reference configuration was adjusted using the standard values, in accordance with the NS 3700 [7]. Standard values for the different parameters were used as a reference, and variations around these were then made based on the data found in the literature [7, 18].

The aim of this study was to investigate the influence of occupant behavior on energy use of the ZEB building and to identify the difference between the values recommended by standards and custom habit based energy use patterns. The literature review indicated that the most common occupant habits are associated with the windows openings – to improve indoor air quality, switching of lighting, use of electric appliances, and DHW needs. Therefore, the text below provides the details of the occupancy patterns and the models related to these elements.

2.1. Occupancy patterns

Appliances and light use together with the window opening and set temperature values are dependent on the occupancy in the dwelling. Therefore, the occupancy patterns are introduced first. The occupancy patterns were assumed as in Fig. 1. Different occupancy patterns were assumed for different rooms. The dwelling was analyzed for four persons.

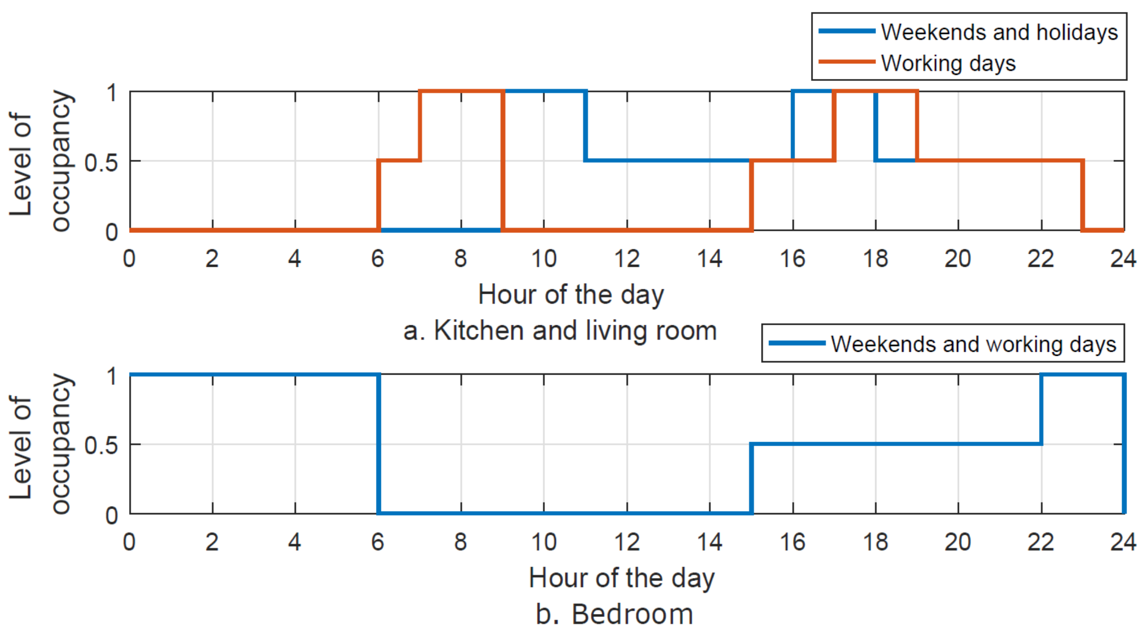

Fig. 1. Occupancy patterns

2.2. Window opening model

The literature review performed by Fabi et al. [19] highlighted that the window openings are influenced by many factors, which interact in complex ways. It is evident that the window opening behavior has a very big impact both on the indoor environment and on the energy use to maintain the desired indoor environment quality. The window opening is not only an important determinant for ventilation, but it also has a direct impact on contaminant concentration levels indoor [20]. The outdoor temperature, indoor temperature, relative humidity, and the indoor CO_2 concentration are found the most influencing variables in determining the opening/closing probability [21, 22].

The research within the IEA – ECBCS Annex 8 [23] shows that in the temperature range between -10ºC and +25ºC, there is a direct linear correlation between the window use and the outdoor temperature. Similarly, the results of statistical analysis in Danish dwellings [24] shows that there is a direct link between the windows opening behavior and the outdoor temperature. Raja et al. find that a change in window opening start to occur at an outdoor temperature of 15ºC [25]. When the outdoor temperature was below this value, fewer windows are opened and opposite when above 15ºC. The results of Nicol showed good agreement with this [26]. However, the study performed in [27] mentioned that the equations for comfort temperatures are different when the building is being heated and when it is free-running, because the indoor temperature is decoupled from the outdoor temperature by the heating controls. Therefore, the windows opening could occur at a temperature of +10ºC [28] as a marking point of the comfort temperature to the outdoor temperature.

Anderson et al. [29] found that CO_2 concentration is the most important driver for opening windows, while the outdoor temperature is the most dominant driver for closing windows. The study of Jeong et al. [30] showed that in the non-heating period, occupants opened windows longer and more frequently and it results in lower CO_2 concentration. The CO_2 concentration is used as an indicator of the occupancy in the rooms where the measurements take place. If the CO_2 concentration is below 420 ppm, the window is closed. The value of 420 ppm is chosen based on observations that the outdoor concentrations may reach levels of up to 400 ppm [22]. The upper bound of CO_2 concentration is normally set to 900 ppm.

The study of Andersen et al. [22] showed that indoor relative humidity was one of the variables influencing the opening/closing probability even though it was in the range 30% - 70%, where humans are modestly sensitive to relative humidity.

One aspect that affects the air change rate is how often and for how long the windows are opened but also the degree of opening will have an impact [19]. Opening a window by more than a few centimeters often produces a rapid influx of the air restricted to a relatively small volume of the house for a transient period of a few minutes followed by a steady air change rate for the house as a whole [20]. Typically, the maximum of window openings occur in the morning [23]. However, due to cocking, cleaning and getting fresh air, the windows can be opened randomly. Brundrett shows that the open windows are most commonly found in the bedroom, particularly the main bedroom, while the sitting room, kitchen and the dining room have the lowest frequency of open windows [31]. Occupants in un-air-conditioned space open windows for two main reasons: 1) to improve indoor air quality or to bring a cooling effect by dropping the indoor temperature and 2) to stimulate indoor air movement [30]. As it can be seen, the occupant's habits play an important in windows opening probability. Therefore, the occupants schedule is required to understand the windows opening or closing behavior in residential buildings [30].

The model of the window opening control employed in this study was based on the literature review and factors leading to opening and closing probabilities. The implemented model for the window opening consisted of the five controllers based on the CO_2 concentration, relative humidity, the outdoor temperature, the indoor temperature, and occupancy schedule. Each control is IF-THEN type, depending what is the action. In some cases there are also some other limits as explained below. Here is a brief description how each of them is working:

- *The CO_2 control* specified the upper and lower levels of the CO_2 concentration. The values were set 400 ppm as the level of the outdoor CO_2 concentration and 900 ppm for the maximum room concentration when occupants were in the room [32].
- *The indoor temperature control* aimed to decrease the room temperature if the indoor temperature was higher than certain limit. The temperature in the kitchen ranged between 18-21ºC with the set point for the window opening of 19ºC. For the living room these values were 20 - 24ºC and the set point for the window opening of 22ºC. For the bedroom, the range was 19 - 21ºC and the set point for the window opening of 21ºC. The room temperature control was coupled with the outdoor temperature sensor that worked only if the outdoor temperature was lower than the indoor temperature. This measure helped to avoid overheating during the summer days.
- *The humidity control* identified the upper and lower bounds for operation between 50 - 65%.

- *The occupancy level* - all the three controllers described above were depended on occupancy in the zone. If the occupants were present the controller sent positive signal, if not a negative signal was sent for the window opening.
- *The outdoor temperature control* operated only if the outdoor temperature was above +12ºC, since the literature review identified lower probability of windows opening in the range of -15 - +10ºC depending on investigated countries.

In addition, the special schedules for windows opening and closing was set for bedroom and kitchen. Windows were opened in the evening and in the morning in the bedroom to get some fresh air and in the kitchen when cooking took place. Since the window position is important and effects the air change rate in the zone, the windows were set to be opened 100% width and 10% height. The state windows condition included two positions: “on” - 1 and “off” - 0. The transient condition was not investigated.

2.3. Model for the domestic hot water use

A number of factors, which are complicated to define and are strongly fluctuated over time, influences the DHW use. Many primary functions such as occupant behavior, occupancy rate and number, demographic condition, appliance, ownership could be the reason resulting in variation of the DHW use [33]. In this section both model based on occupant behavior and the standard model are introduced. The standard model was developed based on the specific annual heat demand and use patterns, while the occupant behavior model was developed based on the water use and statistical data on the real DHW use.

In order to make our study realistic, it was important to find relevant DHW profiles for residential buildings. Different profiles for the DHW were found in the literature, but the most relevant DHW profile was presented in a Finnish study [34]. The DHW profile analysis is based on actual consumption data of the 86 apartments with 191 occupants. This Finnish study consider the month November and August as the representative months for summer and winter. In our study, the DHW profile was adopted for the case of four occupants in the residential building. Fig. 2 shows generated DHW profile considering occupant behavior used in our study.

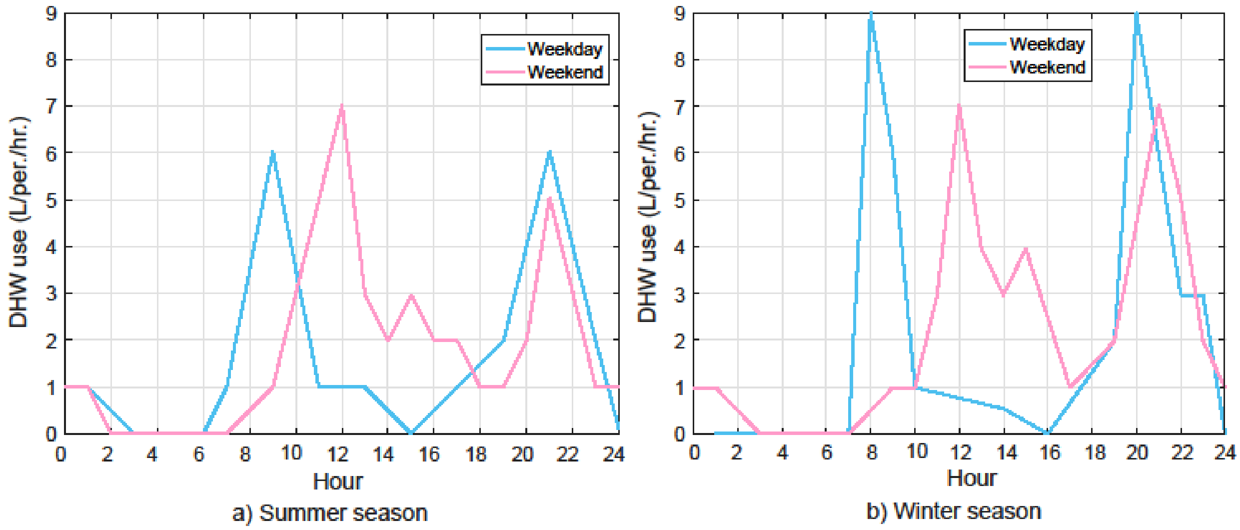

Fig. 2. DHW profile for four occupants in the residential building stock under two seasons

In this study the standard values of the DHW energy use per m^2 as suggests Norwegian standard [35] were not employed, instead the DHW consumption rate of apartment building based on the Norwegian building code was used. This value was set to 40 l/person/day [36].

The standard values for the DHW were used in the reference model. The standard model was modeled by assuming that the average hot water use was 29.8 kWh/m^2 per year with the use profiles as in Fig. 3.

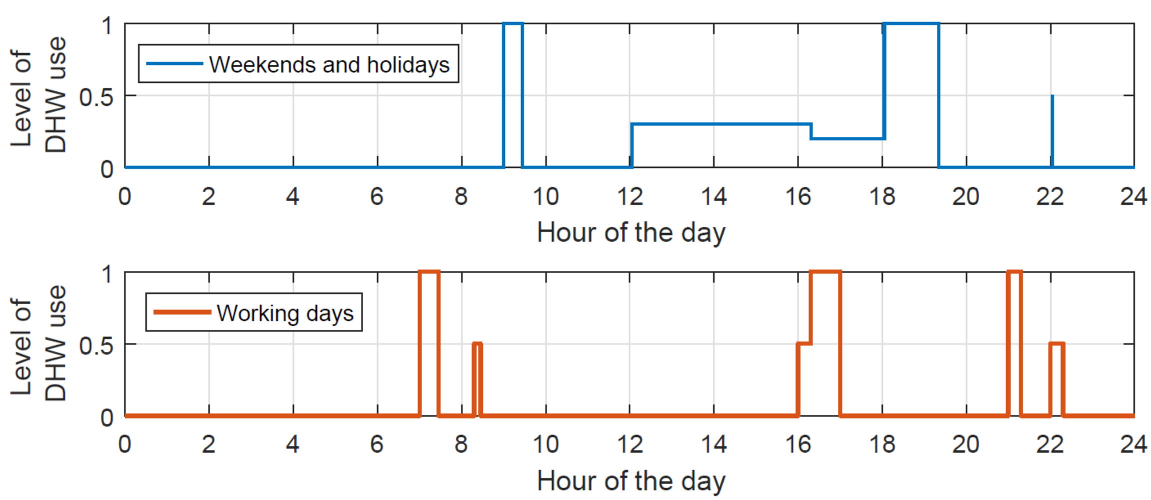

Fig. 3. Domestic hot tap water use profiles based on the standard values

The DHW was prepared and delivered by the energy supply system introduced in Section 3. The supply water temperature for the DHW was set to 55°C, based on the standard requirements [37].

2.4. Model for use of electrical appliances

There is a great variation in the annual electricity use of the dwellings. Dwellings located on the same site and with similar built form have notably different annual electricity use [10]. Electricity use patterns for dwellings are highly stochastic, often changing considerably between customers [38]. These patterns are determined by two main factors: the type and number of electrical appliances in the property; and the use of these appliances by the occupants of the building [10]. Occupancy period and behavior vary widely between households; some have very regular habits while others are much more chaotic [39]. The relationship between total number of appliances owned and electricity use has been the subject of extensive research [40]. Therefore, in our study the model of electrical appliances for residential building was based on data generated with the help of high resolution energy demand model described in [41]. This model for electrical appliances is a high-resolution model that is based upon activity probability [41]. One example of the electrical appliance use based on the model from [41] for kitchen is given in Fig. 4 for summer and winter periods. Please note that the model was built based on statistical modeling and the results were coming randomly. The input data for the installed power of the electrical appliances were based on the survey about the most typical home appliances and energy certificate of the appliances [42]. The survey about appliances use is performed among passive house owners in Norway [42].

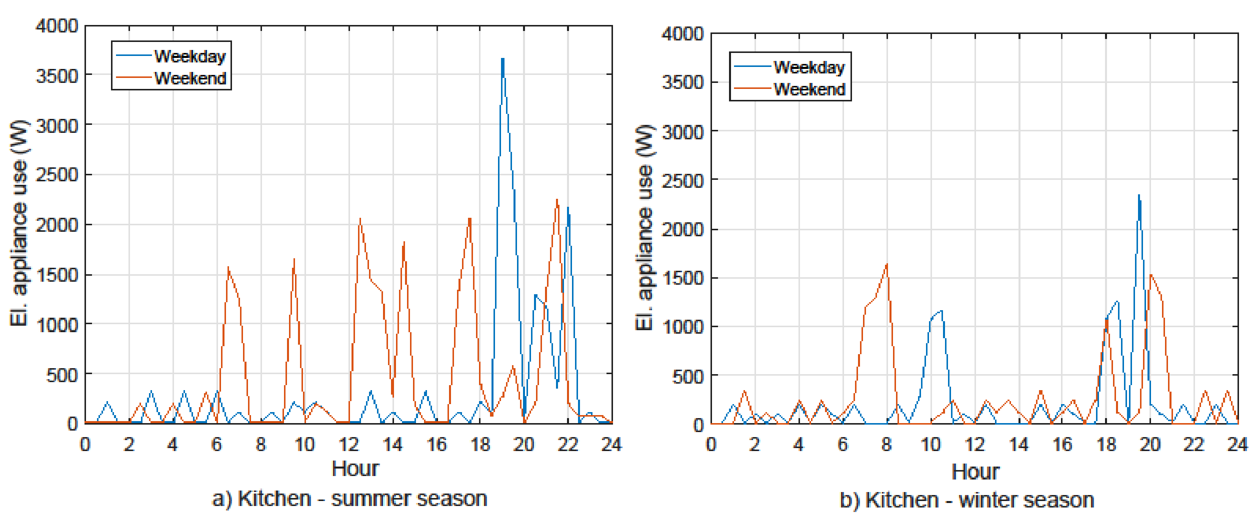

Fig. 4. Electrical appliance use in kitchen

The appliance model explained in [41] uses the appliance as the basic building block, where "appliance" refers to any individual domestic electricity load, such as a television, washing machine or vacuum cleaner. In our study, the 1-min resolution data was reduced to 30-min demand data, since the study did not aim to make very detailed electrical equipment model. The profiles were generated for weekdays and weekend days for each month that showed occupancy patterns in detail. The general number of appliances employed were nine in the kitchen, four in the living room, and five in the bedroom, see a detail appliance list in Table 1.

Table 1 Distribution of appliances in the dwelling

Kitchen	**Living room**	**Bedroom**
Fridge freezer	HI-FI	Clock
Refrigerator	Vacuum cleaner	VRC/DVD
Oven	TV1	TV2
Microwave	TV receiver	Iron
Kettle		Personal computer
Small cooking		
Dish washer		
Washing machine		
Washer dryer		

2.5. Light use model

Human perception of the natural light level within a building is a key factor determining use of electric lighting [43]. Studies have shown that the two main factors affecting lighting energy use are outdoor illuminance and occupant behavior [44]. Behavior factors have a significant influence on luminous comfort among people. People often use internal shading and artificial lighting to adjust and improve the indoor luminous environment, and these different activities influence their levels of comfort [45]. Further, occupants respond to various, often sudden environmental stimuli, triggering manual changes in artificial light use, in turn affecting electrical energy use and demand [46].

In this study, the lighting in the analyzed model was controlled via a fixed schedule combined with occupancy in a particular zone. The illuminance level was set to 200lx in the kitchen and living room and 100lx in the bedroom [47]. The dwelling illuminance threshold is compared against the current level of outdoor illuminance at each time step. If the current illuminance is below the threshold then the resulting value of this test is 1, otherwise 0. In addition, the occupancy in the zone was included in the model, leading to switching the light off when nobody was present.

Another model of the domestic lighting was also implemented based on high resolution lighting profiles generated with the help of the model described in [48]. The light model described in [48] is developed by the same authors as the model for the electrical appliances [41] and is also based on probability. The 1-min data was reduced to 30-min data and profiles were generated for weekdays and weekend days depending on month and occupancy in the zone. Fig. 5 shows an example of generated light profile for kitchen under summer and winter seasons by using the model described in [48].

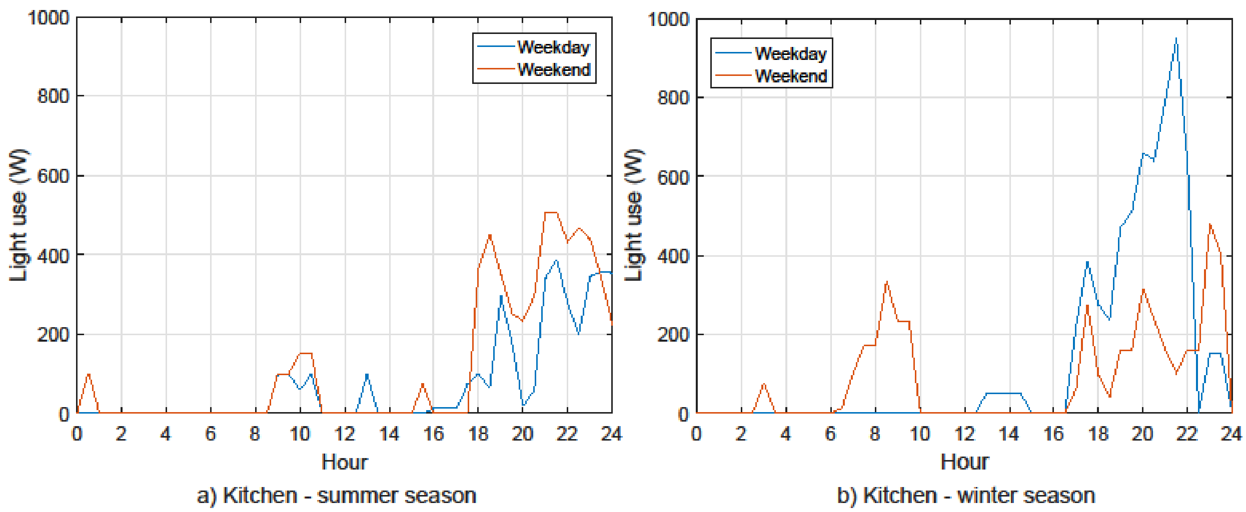

Fig. 5. High resolution lighting model

The results on domestic lighting for both models in our building will be discussed.

2.6. Data analysis and the results presentation

The developed model and the huge amount of the input data enabled big amount of highly relevant results for both energy and indoor air quality analysis. The indoor air quality results were analyzed on hourly level. The energy use data were analyzed on month level. For the electricity grid interaction, a few new indicators were introduced.

In order to give some criticism to this study, the power mismatch and annual energy balance indicators described in [49] were investigated for the results obtained in this study.

The power mismatch and the annual energy balance could be estimated using hourly-average power generation of the PV and the hourly average electricity consumption. The power mismatch introduced in [49] can be calculated as

$$Pow_{mis,i} = Pow_{PV,tot,i} - Pow_{con,tot,i} \tag{1}$$

where $Pow_{mis,i}$ (kW) is the power mismatch of the ith hour, $Pow_{PV,tot,i}$ (kW) is the total hourly-average PV power generation of the ith hour, and $Pow_{con,tot,i}$ (kW) is the total hourly-average building electricity use of the ith hour.

The annual energy balance reliability can be found as:

$$\varphi_j = \frac{\sum_j^{8760} Pow_{PV,tot,i}}{\sum_j^{8760} Pow_{con,tot,i}} \tag{2}$$

where, φ_j is the annual energy balance reliability of the jth year.

The grid stress S is used to describe stress put on grid by the power mismatch, i.e. by the bigger electricity generation from the PV then the building demand. A larger grid stress value presents heavier stress on the grid caused by the ZEB. The grid stress is defined using the grid interaction index [50] as:

$$S = STD\left(\frac{Pow_{mis,i}}{max\left[\left|Pow_{mis,1}\right|, \left|Pow_{mis,2}\right|, \ldots, \left|Pow_{mis,8760}\right|\right]}\right) \tag{3}$$

3. ZEB demo building

In this study, the influence of occupant behavior on a single-family demo dwelling (SFD), called “Multikomfort”, was analyzed. The building was constructed according to the Norwegian Zero Emission Building definitions with an ambition level of operation and material, and is located in Larvik, southern Norway. The annual average temperature in Larvik is 6.3°C. The house is a two-story home with a floor area of 202 m^2, and it was designed to accommodate a family of four to five members. The analyzed building is shown in Fig. 6. A detail building description and parametric study of the analyzed ZEB in Fig. 6 may be found in [16, 51].

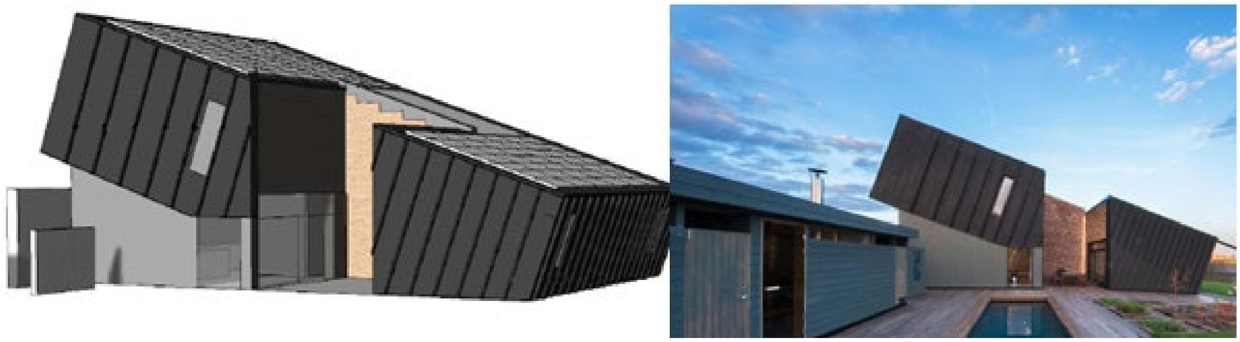

Fig. 6. Architecture of the SFD "Multikomfort" [52]

U-values for the external walls, the roof, and the external floor were set in accordance with the requirements stated in [7] for dwellings of passive house standard. The U-values and the normalized thermal bridge values are given in Table 2. The total U-value of the windows was calculated to be 0.63 W/m^2K.

Table 2. U-values and normalized thermal bridge values

	Values
External walls	U = 0.10-0.12 W/m^2K
External roof	U = 0.08-0.09 W/m^2K
Slab on ground	U = 0.07 W/m^2K
Windows	U = 0.65 W/m^2K
Doors	U = 0.65 W/m^2K
Normalized thermal bridge value	Ψ = 0.03 W/m^2K

The heat supply system consisted of flat plate solar thermal collectors (STC) in combination with a ground-source heat pump (GSHP) and an exhaust air heat pump (EAHP) for the heating and cooling, and production of DHW. The energy supply of the SFD was mainly covered by renewable energy sources on site. Excess solar heat was used to recharge the GSHP boreholes. DHW was preheated by the solar collectors, and after heated by the EAHP. The electric heaters were installed to cover additional heating demand. Ventilation air was heated directly from the ground source heat exchanger, while the space heating was designed as floor heating. The PV system was used for production of electricity and was integrated into the roof along with the STCs. The PV system utilized electricity grid for storage and was sized to produce the same amount of electricity as consumed by the building under the standard conditions. An overview of the heating and cooling system, excluding the PV panels is given in Fig. 7.

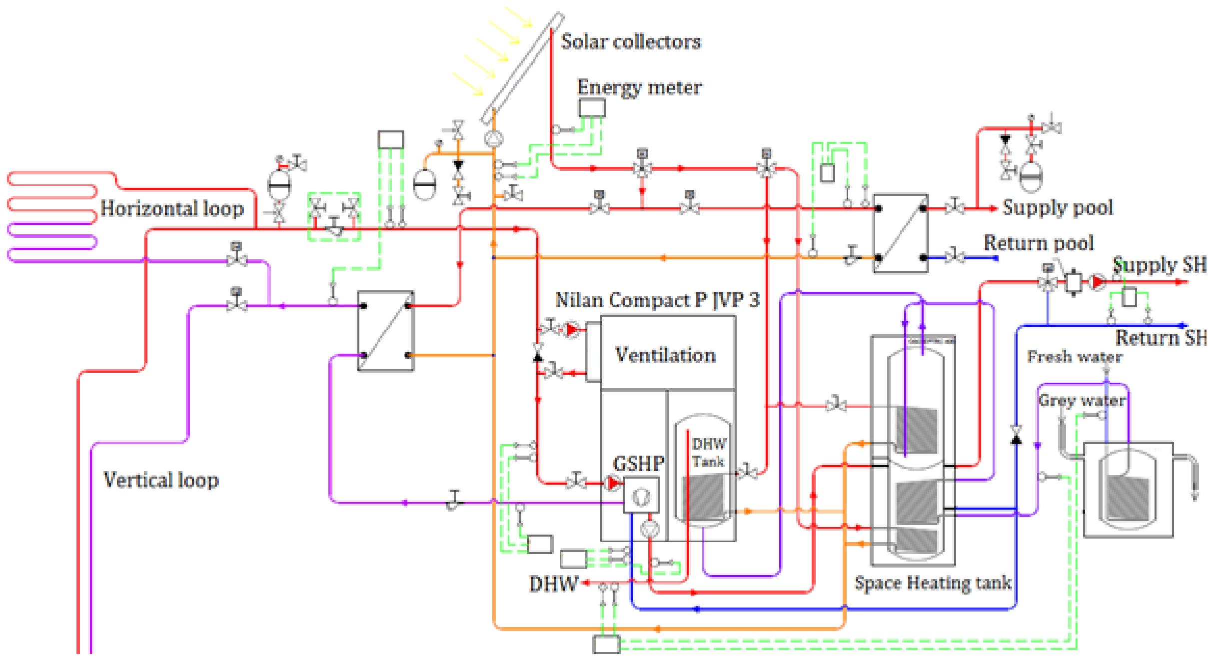

Fig. 7. Heating and cooling system with solar thermal system, GSHP and EAHP

The implemented ventilation system was balanced mechanical Constant Air Volume (CAV) system. Flow rates were set to 240 m^3/h. U-values for all constructions except windows were set according to the standard values [7], while the U-value for the windows was 0.63 W/m^2K.

The solar, ground, and exhaust air heat were recycled in heat pump units. When the temperature at the bottom of the DHW storage tank was above the specified limit of 60°C, the extra solar heat was used to charge the GSHP boreholes. Any heat which could not be used either for heating of DHW or charging the boreholes was transferred to the SH tank during the heating season. Basic design parameters for the energy supply system are shown given in Table 3. The data in Table 3 are based on the rated values for the component and they were provided from the building documentation. The PV system capacity was evaluated to provide enough electricity on annual level for the analyzed dwelling [16].

Table 3. Basic energy system design parameters

Indoor/outdoor design temperatures		20°C/-17°C
Boreholes	Number	Depth
	1	80 m
GSHP	COP	Heating capacity
	4.6	3 kW
Solar collector	Collector area	Efficiency

	16.75 m^2	60%	
EAHP	Air/air	Air/water	
COP	4.6	3.9	
Heating capacity	2.0 kW	1.2 kW	
DHW tank	Volume	Electrical supply	
	180 L	1.5 kW	
SH storage tank	Volume	Electrical supply	Heat loss
	325 L	3.0 kW	2.0 kWh/day
PV panel	Size	Efficiency	
	37.75 m^2	20%	

4. Results and analysis

Influence of the occupant behavior on the ZEB performance is presented in this section. The analysis of the influence of the occupant behavior included analysis of the following: heating and cooling demand, indoor environment parameters, and electricity grid and grid interaction. Result comparison of different approaches to model the occupant behavior is also given in the section.

4.1. Influence of the occupant behavior on energy demand

First, Fig. 8 shows results on heating and cooling loads in the investigated ZEB. “OB” shortcut is used to mark the results treating the occupant behavior. Maximum specific heating demand was calculated, in accordance with the NS3700, to be 17.6 kWh/m^2.

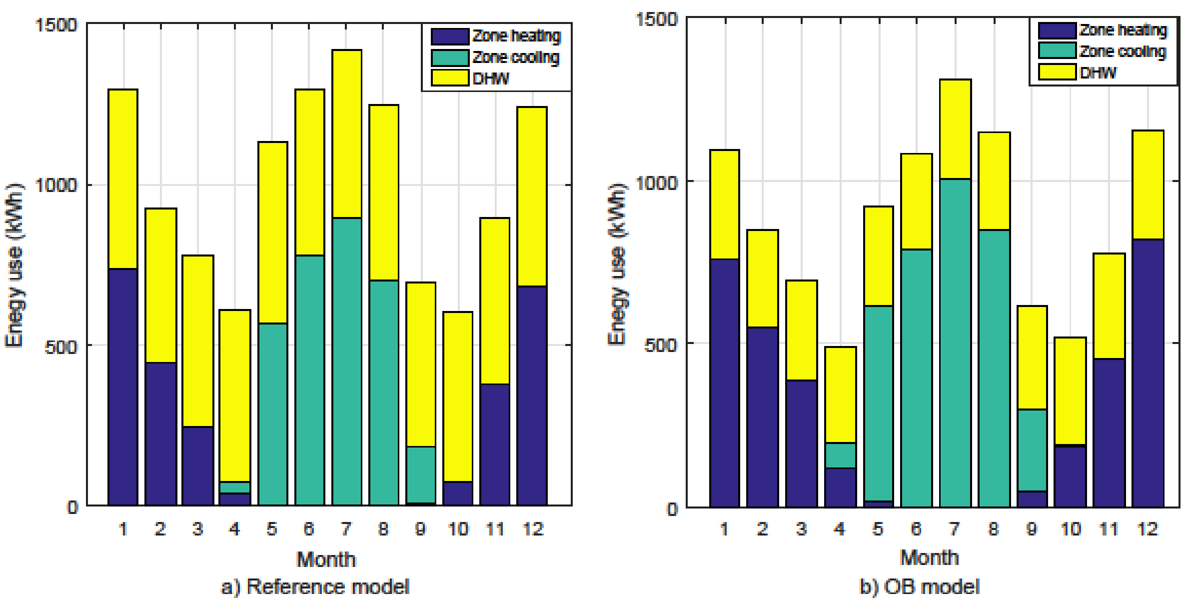

Fig. 8. Heating and cooling loads

From Fig. 8 it can be noticed that there is a difference between the results for the reference case and the model treating the occupant behavior (marked with OB model). It was found that DHW profiles suggested by Norwegian standard NS3700 [35] gave higher values for the DHW energy use compared to the results obtained by using the occupancy profiles from [34]. The DHW model treating the occupancy resulted in 3745.1 kWh/year, while the reference case based on the standard values gave 6368.7 kWh/year. The difference in these values was 70%. This showed that the standard values may lead to oversizing the system and overestimating the DHW energy use. The reason for this difference could be that the Norwegian standard NS3700 does not consider coincidence factor for the DHW use. The standard values for the DHW considers that all the DHW taps would be in use. In practice, most of them are not in use. This big difference in results might indicate that the standard treats coincidence factor to be 1, while in practice for the DHW this factor is low. Further, the heating load in the occupancy model showed higher values in comparison with the reference case. The heating load in the reference case was 2609 kWh/year, while when considering the occupant behavior it was 3347.2 kWh/year, that is 28 % more. The reason for this was that more heating was required when the windows were opened during the winter season. Opposite happened for the cooling load that was 3959.7 kWh/year for the reference case and 3570 kWh/year when occupant behavior was considered. This means that the occupant behavior introducing window opening decreased cooling load for 11 %.

Fig. 9 shows the results on electricity use for the reference and the occupant behavior model. Please note that in Fig. 9 the results for the OB model for the lighting considered the presence schedule and the lighting level. Further comparison between this occupancy model and the stochastic model in given in Fig. 10.

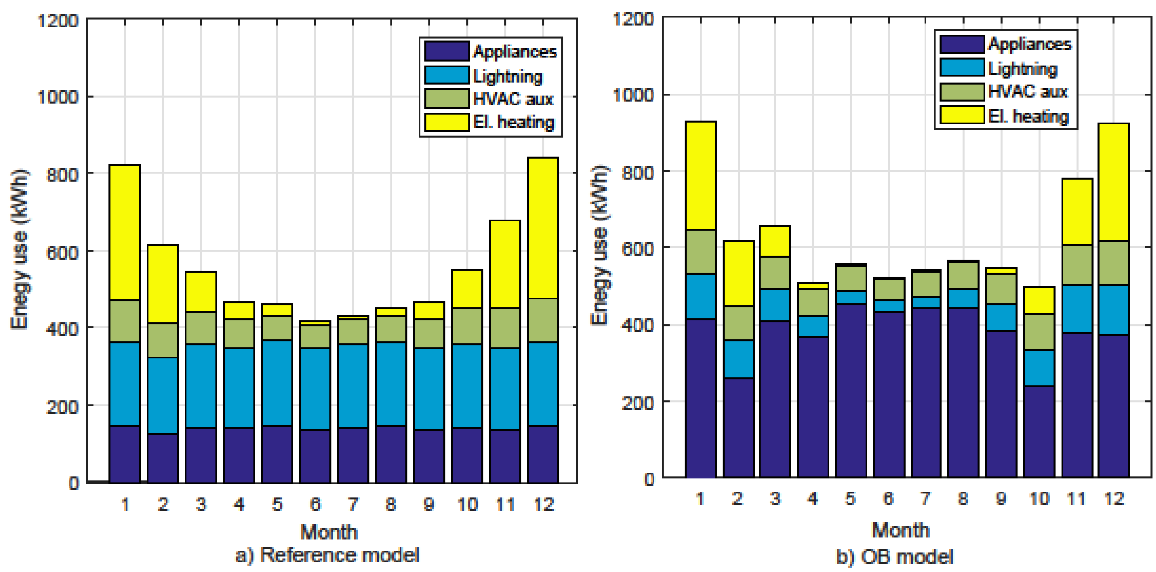

Fig. 9. Electricity energy use

Fig. 9 shows that in the reference case the lighting and equipment electricity use had a uniform distribution along the year. However, the detailed occupancy model resulted in much higher values for the appliances, but lower for the lighting. The reason for the low lighting values could be that the lighting model used to provide the results in Fig. 9 did not include stochastic nature of human behavior. The difference in the electricity use for the HVAC auxiliary equipment was less than 1%, while for the electrical heating it showed 31.4% - higher for the reference case. Finally, the total electricity use for the occupancy behavior model was 17% higher than for the reference case. In order to give criticism to the implemented lighting model and possible deviation in lighting energy use, the study further gives comparison with the model found in [48]. This model is developed for the UK conditions and employ stochastic nature of the human behavior. Fig. 10 shows the lighting energy use comparison for the implemented occupancy model and the stochastic model.

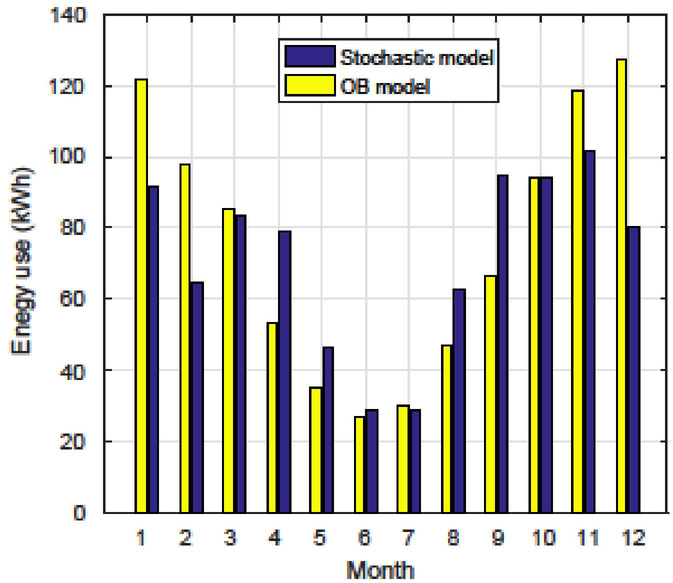

Fig. 10. Comparison of two lighting models

The results in Fig. 10 show that the difference for the stochastic model and the occupancy model was relatively small. The annual electricity use for the occupancy model combined with outdoor illuminance developed in IDA-ICE showed 905.1 kWh of electricity, while the model introduced in [48] resulted in 834.4 kWh. The difference was 7.8% on annual level, which gives a conclusion that the occupancy model for lighting could be treated as reliable for the further analysis. The reason for a bigger difference in the lighting energy use during winter months might be due to location. To recall, the occupancy model marked with the OB model in Fig. 10 was based on the occupancy and the light level in Oslo, Norway, while the stochastic model in [48] was developed for the conditions in UK. The outdoor lighting conditions are very different in Norway compared to UK, with long and dark nights in the winter. Finally, it can be concluded that the results for the lighting energy use marked with the OB model in Fig. 9 could be treated as reliable for the further analysis.

4.2. Influence of occupant behavior on indoor air quality

The indoor air quality level is very important to consider in the ZEB, since it provides relevant information about human perception in the investigated building. The indoor air temperatures and CO_2 level are two important factors among many explaining indoor air quality and are given further. Fig. 11 shows CO_2 level versus air flow rate. Please note, that in Fig. 11 the red color shows the results for the reference case, while blue color presents changes due to occupancy activities, i.e. window openings.

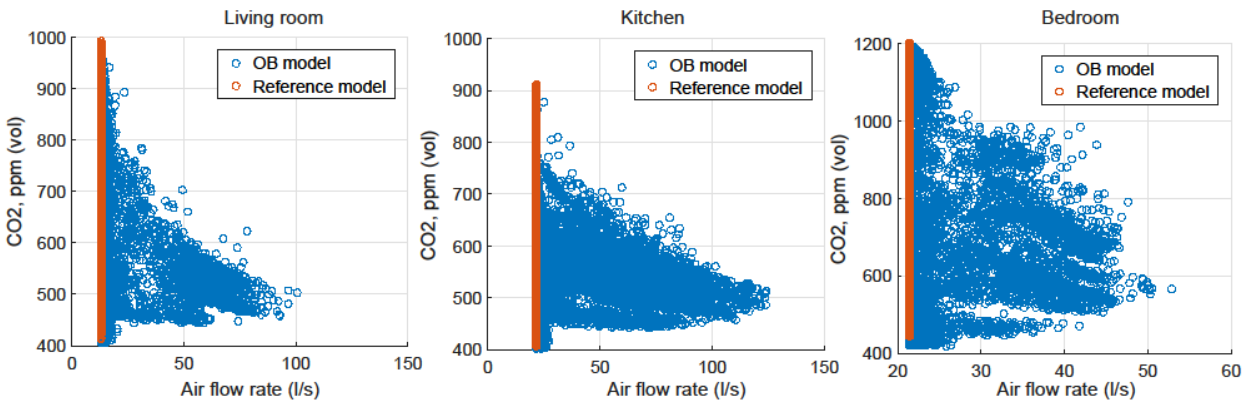

Fig. 11. Change in CO2 level in zone

To recall in Fig. 11 for the reference case, the mechanical CAV ventilation was only implemented. This resulted in the air flow rate of around 20 l/s depending on the investigated zones, based on the standard requirements as explained in Section 3. However, when the occupant behavior was considered, the results showed reduction of the CO_2 level with the increase in the air flow rate. The air flow rate increased due to window opening. This fits well with the human sensation and dissatisfaction of indoor air quality and the human reaction to open the window if they feel dissatisfied. In the occupancy model, the CO_2 threshold was set in the range of 700 – 1100 ppm for the mechanical ventilation. In Fig. 11 it can be noted that the upper bound for the CO_2 concentration was reached only in the bedroom, when the room was not occupied and the windows were not operated. However, while the bedroom was ventilated in the evening and morning hours the CO_2 level decreased considerably due to window openings. Further, the temperature fluctuation within the room was important to consider, since it indicated achieved thermal comfort. Fig. 12 shows temperature distribution with and without considering the occupancy model.

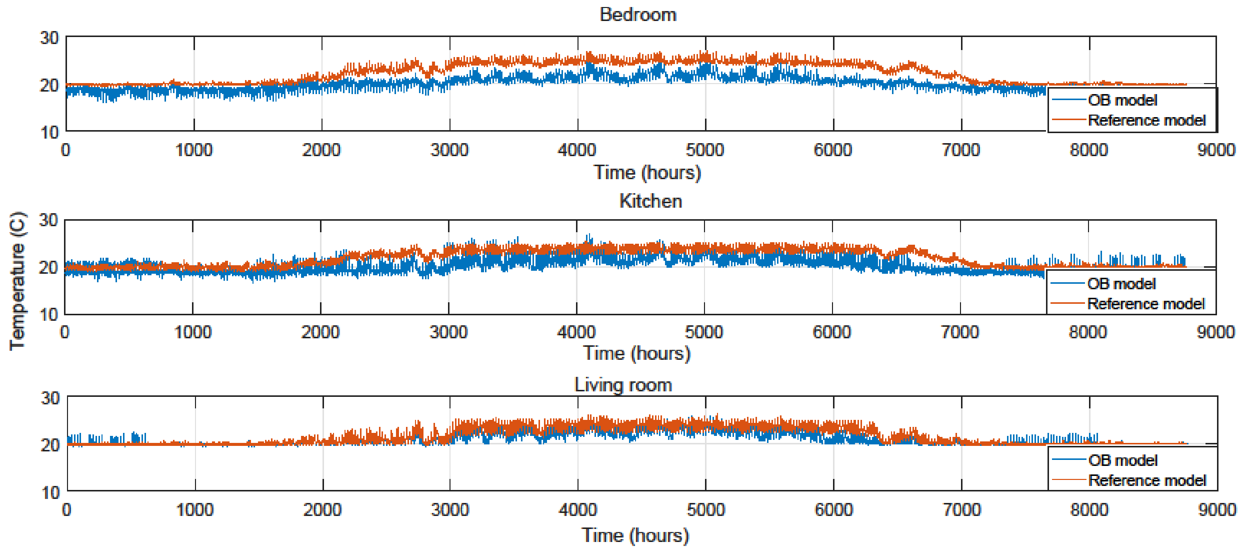

Fig. 12. Temperature distribution in the zones

Fig. 12 shows that in the reference case the temperature in the zones was close to upper bound of threshold. However, the opposite was found in the occupancy model, because the occupants open the window whenever they felt a bit dissatisfied.

4.3. Influence of window openings on heating and cooling demand

Different studies indicate that the number of windows opened in the building results not only in a more effective cleaning of pollutants and improving of indoor air quality, but also affect energy use in building. For this reason, it was of interest to make comparison on building energy use under different windows opened conditions. Fig. 13 shows the results on heating and cooling energy use due to number of opened windows.

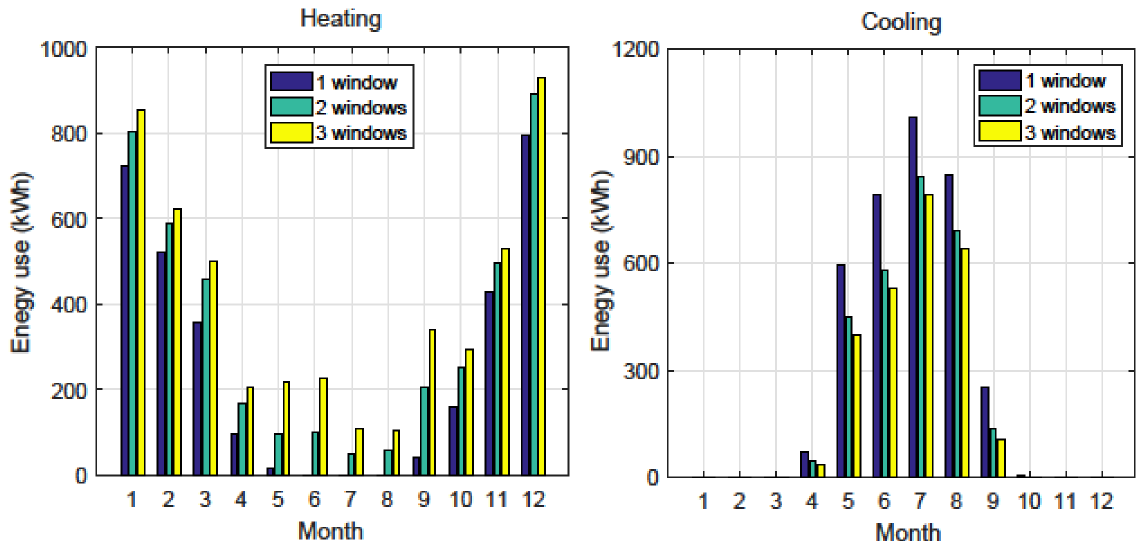

Fig. 13. Heating and cooling energy use depending on number of opened windows simultaneously

The results in Fig. 13 shows that the number of windows opened simultaneously affected heating and cooling loads. Since the windows' sizes were different in the zones, the heating and cooling loads changed randomly depending on the window that was opened. In the scenario where two windows were opened simultaneously, the highest heating load was found when the two largest windows were operated together. At the same time this resulted in lower cooling load for the plant, since cooling by natural ventilation was implemented. The difference in heating energy use constituted 32.8% for two windows configuration and 57.28% for three windows configuration in comparison with the case when only one window was opened for the occupant's needs in each zone. In the cooling mode, the three windows configuration showed reduction of the cooling energy use by 20.2%, while the two windows configuration resulted in 12.5% of saved cooling energy.

4.4. Influence of the occupant behavior on the electricity grid interaction

One of the most important questions when it comes to ZEB is the ability of a building to satisfy electricity needs with the help of installed PV system. Therefore, analysis of the ZEB influence on the power grid was performed. Due to intermittent power generation from the ZEB, the stress that could be caused to the grid is inevitable. Therefore, it is of high importance for power distribution companies to be aware of this effect from the areas with the ZEB. The electricity use and generation was distributed as shown in the upper subplot of Fig. 14 and Fig.

15. While the lower subplots in Fig. 14 and 15 show the mismatch factor calculated as the ratio between the generated electricity and used.

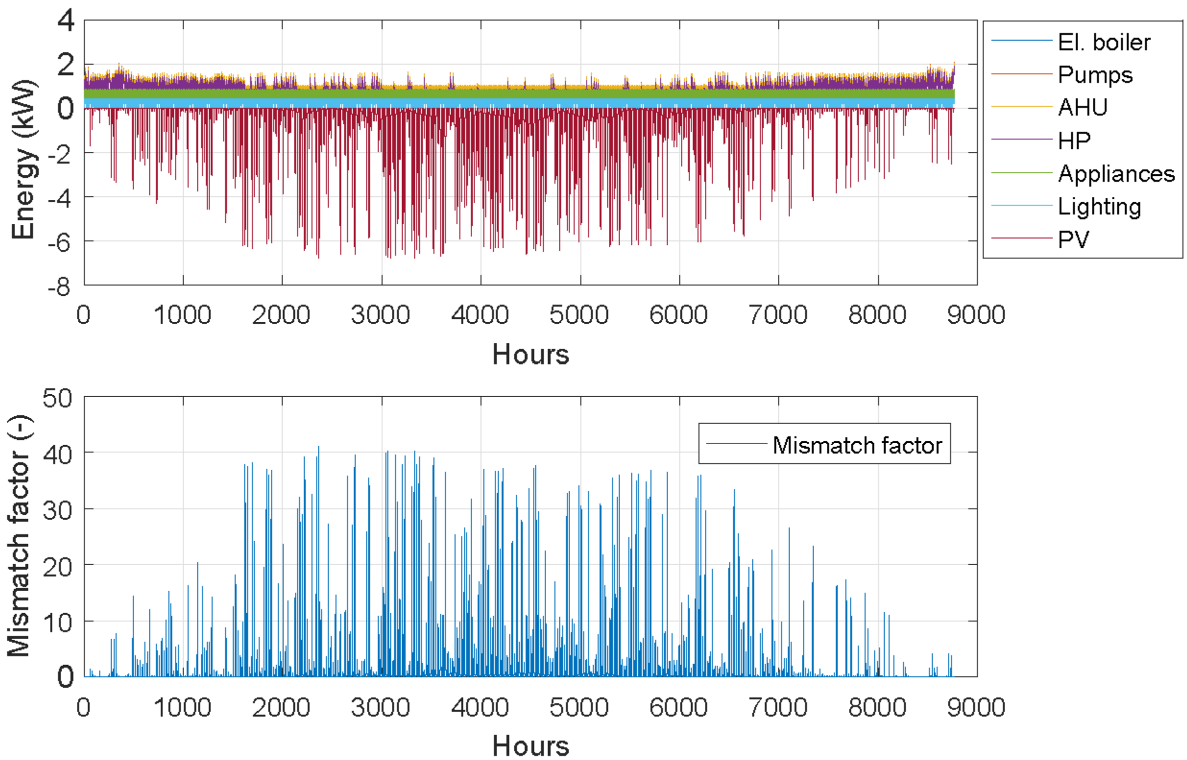

Fig. 14. Electricity use, electricity production, and mismatch factor for reference model

The reference model showed that lighting and electrical equipment marked “Appliances” resulted in a highest electricity load on annual basis, while the smallest was due to circulation pumps. Further, it can be noticed that the annual load for all components was less than 2 kW. This led to high mismatch factor of power generation by PV, which varied from 0 to 42. However, the results for OB model showed different picture, see Fig. 15.

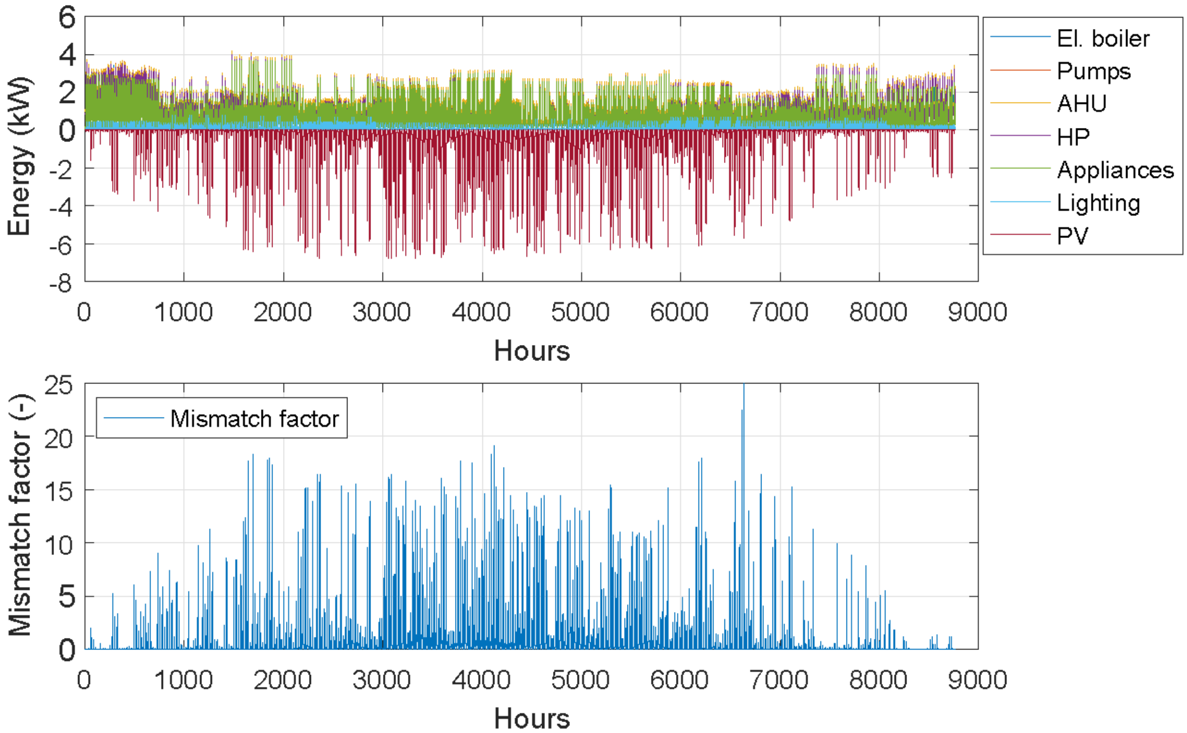

Fig. 15. Electricity use, electricity production, and mismatch factor for OB model

From Fig. 15 in can be seen that the annual electricity load showed increase up to 4 kW. This is mainly because of stochastic nature of human behavior that resulted in higher values for electric appliances and lighting. Simultaneously, the mismatch factor for power generation has decreased from 42 to 25, since less generated power was available. For both models the highest values were identified during the summer season, while the lowest values during the winter season.

Since there is no negative values in mismatch factor subplot in Fig. 14 and Fig. 15, one may argue whether the mismatch factor is a enough explanatory energy performance indicator. By analyzing the lower subplots it is difficult to estimate how big the building electricity demand was in the time when the PV system could not cover the load.

Fig. 16 shows the result on the power mismatch defined in Equation (1) for the case of simultaneous use of the DHW, lighting, appliances, and one window. The results in Fig. 16 are valid for the OB model considering a simultaneous effects of all the introduced models with only one window open, for more details see Section 2. In addition the results for the reference model are presented for comparison.

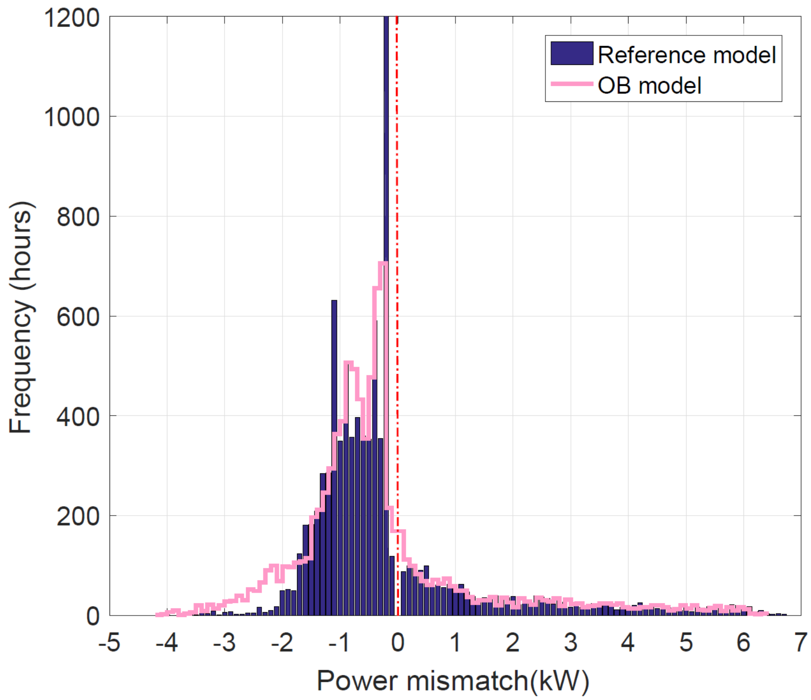

Fig. 16. Histogram of the power mismatch when the occupant behavior was treated

Fig. 16 shows different frequency hours for two models. The average frequency hours where the power generated by the PV was bigger than the electricity demand was 88 hours for the reference case and 112 hour for the OB model. This means that the ZEB had higher electricity production over short periods with the OB model. The total amount of hours with the positive correlation for the reference model was 2 023 hours, while with the negative was 6 737 hours, which is 3.33 times more. For the OB model these values were 6 907 hours and 1853 hours, which resulted in 3.73 times difference. It can be noticed that under the reference model the highest frequency of 1 201 hours was under 0.2 kW of negative electrical load and 631 hours under 1.1 kW. However, with the OB model, the peaks shifted to 0.3 kW for 706 hours and 0.9 kW for 507 hours. This means that the investigated building was largely dependent on the power grid and could hardly be considered energy independent. Therefore, the investigated ZEB considering the occupant behavior showed the results similar with a common residential building (without electricity generation), but not the expected ZEB performance (to generate more electricity than used). This shows that occupancy affects much the energy use in buildings and can lead to change in assigned values of building's energy certification.

The grid stress as a result of different occupant behavior is shown in Fig. 17. In Fig. 17 different shortcuts were introduced to present different scenarios to evaluate the effects of the occupant behavior. In total 31 scenarios for different occupant behaviors were analyzed. A brief explanation for each scenarios is given in Table 4. In some scenarios the occupant behavior models introduced in Section 2 were used, while all the other parameters were kept as the standard recommendations.

Table 4. Scenarios to evaluate the effects of the occupant behavior

Scenarios	**DHW model**	**Electrical appliance s model**	**Light use model**	**Window opening model with one window**	**Window opening model with two windows**	**Window opening model with three windows**	**Standard values**
DHW	x						x
DHW-App	x	x					x
DHW-App-Light	x	x	x				x
DHW-App-W1	x	x		x			x
DHW-App-W2	x	x			x		x
DHW-App-W3	x	x				x	x
DHW-Light	x		x				x
DHW-Light-W1	x		x	x			x
DHW-Light-W2	x		x		x		x
DHW-Light-W3	x		x			x	x
DHW-W1	x			x			x
DHW-W2	x				x		x
DHW-W3	x					x	x
App-Light		x	x				x
App-Light-W1		x	x	x			x
App-Light-W2		x	x		x		x
App-Light-W3		x	x			x	x
DHW-App-Light-W1	x	x	x	x			
DHW-App-Light-W2	x	x	x		x		
DHW-App-Light-W3	x	x	x			x	
App		x					x
App-W1		x		x			x
App-W2		x			x		x
App-W3		x				x	x
Light			x				x
Light-W1			x	x			x
Light-W2			x		x		x
Light-W3			x			x	x
W1				x			x
W2					x		x
W3						x	x

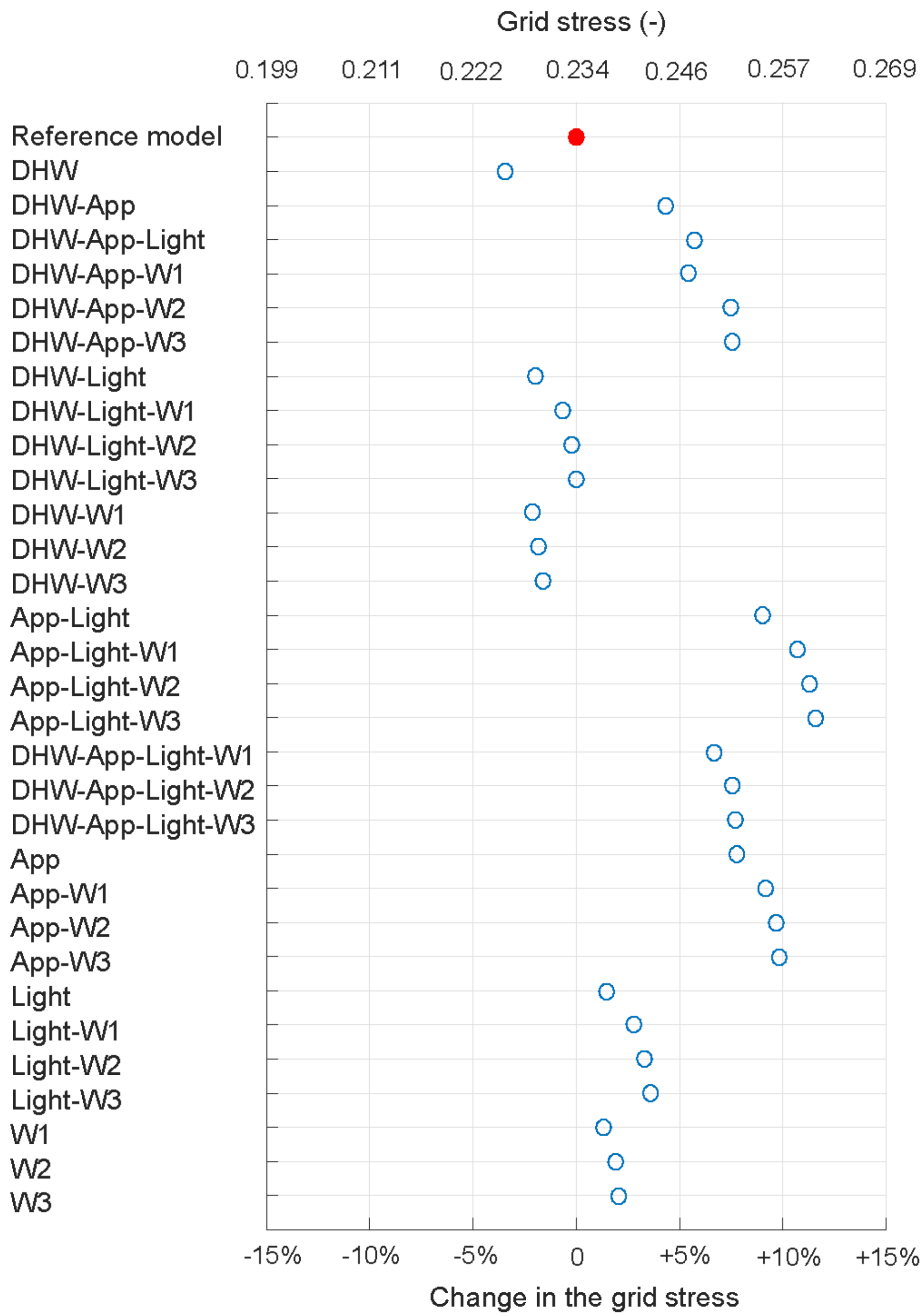

Fig. 17. Grid stress

Fig. 17 shows that the highest grid stress was experienced with the scenario of simultaneous operation of electrical appliances model, light use model, and three window models in each room. This behaviors resulted in 0.261 value of grid stress. This is reasonable, because the lighting and the electrical appliance use are proportional to the total electricity use of the building. The lowest grid stress was due to the use of the DHW. The influence of the occupant behavior on the DHW use resulted in a low value for the grid stress, because the DHW was mostly supplied from the solar collectors and the heat pump.

The low values for the grid stress were also found due to number of windows opened and their combinations with the DHW use. The combinations where all the investigated parameters were evaluated simultaneously, such as the scenarios DHW-App-Light-W1, DHW-App-Light-W2, and DHW-App-Light-W3, gave the grid stress of 0.2496, 0.2516, and 0.2520 respectively. In general, the number of windows opened and use of DHW did not have strong effect on the grid stress due to special aspects of constructed energy system in the investigated ZEB. The overall estimation of investigated parameters showed that the change in occupant behavior models resulted in grid stress variance in the range of -5% – +13% in comparison to reference model.

The results showed that high resolution models for the occupant behavior regarding the appliances and lighting use were highly relevant when the ZEB was analyzed. The extensive analysis of the ZEB considering high resolution models for the occupant behavior will lead to proper design of energy supply system for the ZEB and guarantee that a power shortage would not happen during the peak hours.

Finally, the energy balance reliability is presented in Fig. 18. The energy balance reliability index shows the degree of electricity demand coverage from the PV system on monthly and annual basis. The energy balance reliability figure was calculated by Equation 2. Fig. 18 shows monthly and annually (dashed line) values found for the three scenarios of the occupant behavior presenting the maximum, the minimum, and the average indexes for the grid stress discussed in Fig. 17.

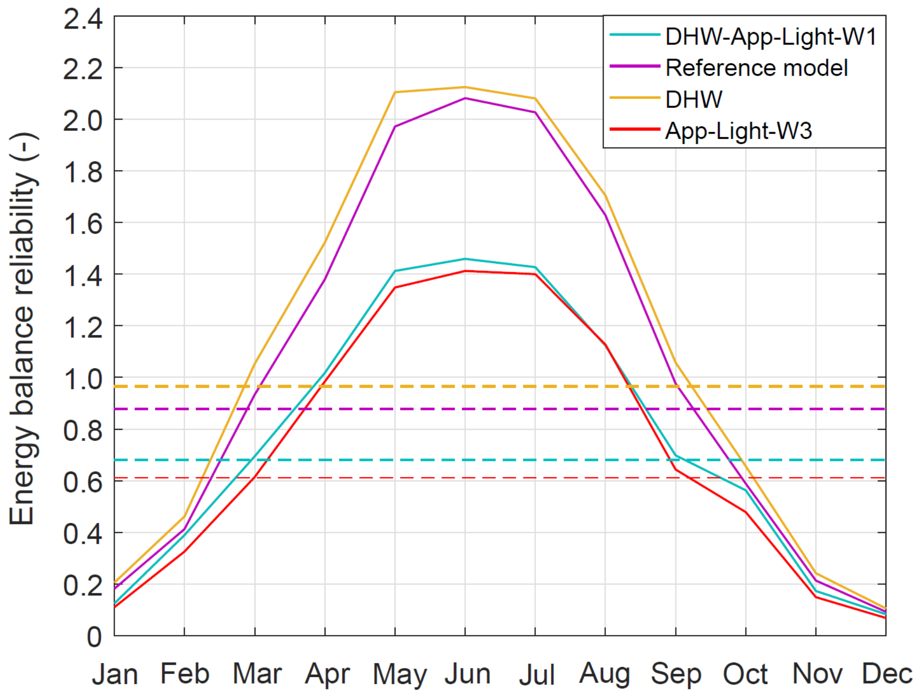

Fig. 18. Energy balance reliability

As it was found from Fig. 17, the maximum grid stress was found for the scenario with the simultaneous implementation of the occupant behavior model for the appliances, the lighting use and three windows, while the smallest was for the DHW occupancy model. Therefore, it can be seen in Fig. 18 that the monthly values under these cases showed the same trend as discussed for Fig. 17. When the value for the energy balance reliability reached index equal to 1, the demand was fully covered by the supply, otherwise, the power from the electricity distribution grid was required.

The energy balance reliability index was above 1 from March to September for low electricity energy use profiles (DHW and Reference model), while for the high electricity use (App-Light-W3) the high values for the reliability index started one month later and ended one month earlier. Therefore, the annual energy balance reliability index was 0.878 for the reference scenario, 0.966 with only the DHW model, 0.679 for the complete occupant behavior model (labeled DHW-App-Light-W1 in Table 4), and 0.613 for the scenario with the simultaneous implementation of the occupant behavior model for the appliances, windows and the lighting use (labeled App-Light-W3 in Table 4).

In general, the annual values for the reference model (0.878) were less than 1, which means that the designed PV panel area was undersized than it might be necessary when occupants would be fully considered. This explains the frequency diagram shown in Fig. 16 where the number of positive hours is less than negative. From the other side, the annual value does not provide indication about power fluctuations on hourly or daily basis, therefore, it is hard to conclude that the installed PV area presents the best match between the supply and the demand. The solution for this could be in installation of electric energy storage system for internal needs during low solar irradiance hours.

5. Conclusions

The first and very important conclusion of this study is: consideration of occupant behavior for better energy use prediction of the ZEB is highly necessary. In this study, this was done by introducing different profiles than the standard values. The analysis on two models with different energy use profiles showed that the occupancy patterns affects significantly total energy use and demand. This is important to consider when the newly constructed building goes through energy certification process. Quite often, the energy use of certified building varies greatly when it comes to real energy use. The main reason for this is that predefined standardized profiles and requirements are employed. In general, most of the standard values are accepted from previous standard versions or some previous requirements, without considering the new way of the building and component use. However, a number of different profiles could be found in the literature and there is no universal one that describes stochastic nature of human behavior. For this reason, consideration of the occupant behavior and challenging the standard values should be employed to improve energy use analysis, when relevant.

The comparison of two models according to Norwegian standard NS3700 and detailed occupancy revealed equal annual energy use distribution when it comes to the HVAC energy use and different annual energy use distribution when it comes to the lighting, the electrical heating, and appliances. This shows that the energy use values provided by the standards and policies do not include all factors on lower level that could lead to change in the building energy use.

The analyzed ZEB showed the annual energy reliability factor equal to 0.679 when all the four components of the occupant behavior were considered, the correct DHW profiles, the electrical appliance use, the lighting use, and the window openings. This value was by 22.5% less than for the reference model. This means that the PV panel area would not be able to cover all the electricity demand, if the occupants use of the ZEB was different than the standard values. Consequently, the ZEB would not fulfill its definition. From the other side, the PV system is normally sized to cover the average annual electricity demand. The solution for improving this could be installation of a electric storage based on design requirements for such systems. Consequently, the peaks would be shaved and the need in electricity supply from the grid would decrease. Economic possibilities in transferring the generated electricity to the grid were not investigated.

In this study, a systematic method how to organize all the influence from the occupants was not suggested. Influence on the components design of the occupant behavior was not considered. These two topic may be motivation for a further research.

Acknowledgement

The authors appreciate the support of funding from the Department of Energy and Process Engineering of the Norwegian University of Science and Technology. The authors gratefully acknowledge the support from the Research Council of Norway and several partners through the Research Centre on Zero Emission Neighbourhoods in Smart Cities (FME ZEN).

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