

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

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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

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

30

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

33

34 **Nomenclature:**

35 $Pow_{mis,i}(kW)$ power mismatch at the i th hour

36 $Pow_{con,tot,i}(kW)$ total hourly-average building power use at the i th hour

37 $Pow_{PV,tot,i}(kW)$ total hourly-average PV power generation at the i th hour

38 $S(-)$ grid stress

39 $STD(-)$ standard deviation

40 $\varphi_j(-)$ annual energy balance reliability at the j th year

41

42 **1. Introduction**

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

52 Zero Energy/Emission Building (ZEB) has become a term for buildings that are self-
53 energy supplied or may even export energy. These buildings are characterized by energy efficient
54 components and energy supply from renewable energy sources [4]. A building may be
55 characterized as a ZEB when it is able to export excess energy generated by renewable sources,
56 for instance by photovoltaic (PV) modules, to the grid and achieve an annual positive net balance

57 between demand and supply. Different ambition levels within the ZEB definitions have been
58 suggested depending on the different emission items included in the calculation [5]. The starting
59 point in a ZEB design is to start from a passive house requirements for building envelope or
60 currently valid national building code. Residential passive buildings are characterized by energy-
61 efficient building envelope. Requirements for specific heating energy use and specific heat rate in
62 dwellings of the passive house standard is 15 kWh/m² and 10 W/m² [6]. However, achieving these
63 requirements is complicated in Norway due to a colder climate compared to Germany, where the
64 passive house standard was first introduced. In Norway, these requirements are stated in the
65 standard that describes necessary prerequisites for passive houses and low energy buildings [7].
66 As a result of low space heating demand, the DHW heating demand presents an increasing share
67 of the total heating demand that correspond to 40-85% in residential passive buildings [6]. This
68 gives the DHW preparation a greater role in modern buildings than before.

69 Stricter regulations for the energy use in buildings mean that the buildings constructed
70 these days are expected to be significantly more energy efficient. However, the measured
71 performance of modern low-energy buildings is often below expectations. Occupant behavior has
72 been found accountable for variances in excess of 50% in use of electrical equipment between
73 design and measurements, and even larger variances when it comes to DHW use. Ventilation rate
74 and indoor air temperature are also found to vary greatly in actual use compared to the desired or
75 set values [8-10]. Simulations of indoor environment and energy use are becoming increasingly
76 important in the design phase of buildings. However, the discrepancies between simulation
77 results and actual energy use may be very big and may be induced by different factors. This
78 difference has become known as the “performance gap” [11]. One of the most important
79 conclusions from the International Energy Agency (IEA) Annex 53 - Total Energy Use in
80 Buildings: Analysis and Evaluation Methods is that the occupant behavior is one of the reasons
81 inducing a significant difference between the simulated and real building energy use [12].
82 Creating simulation models that are able to simulate user behavior accurately has been proven to
83 be difficult, and standardized patterns for use and internal gains are often used [13]. Different
84 methods have been used to model occupant behavior to evaluate influence of the occupant
85 behavior on the building energy use, such as simplified schedules, well defined profiles, and
86 stochastic methods [14]. In the case when it is very complicated to use data-mining techniques to
87 analyze occupant behavior and integrate this into the building simulation programs, use of well-

88 defined user profiles showing standard deviation of the values may be very successful [15]. Since
89 ZEB is connected to the electricity grid, big variations in the estimated electricity use will also
90 influence the electricity grid. For example, it was show that a ZEB located in Norway may
91 perform as a normal building – using electricity from the grid in winter, while in in summer the
92 same building may produce much more electricity than its need [16]. Therefore, the aim of this
93 study was to show change in the ZEB performance caused by the occupant behavior. Due to
94 different occupant behavior both indoor environment and energy performance of the ZEB may be
95 changed. Due to importance of proving the ZEB performance during the building life-time, it was
96 highly important to integrate a complex simulation model of a ZEB and detail occupancy models.
97 In this study both well-developed schedules and stochastic models for the occupant behavior
98 were implemented for the occupant behavior model. That way, it was possible to analyze and
99 understand the change in the ZEB performance caused by the occupant behavior.

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

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

114

115 **2. Methodology**

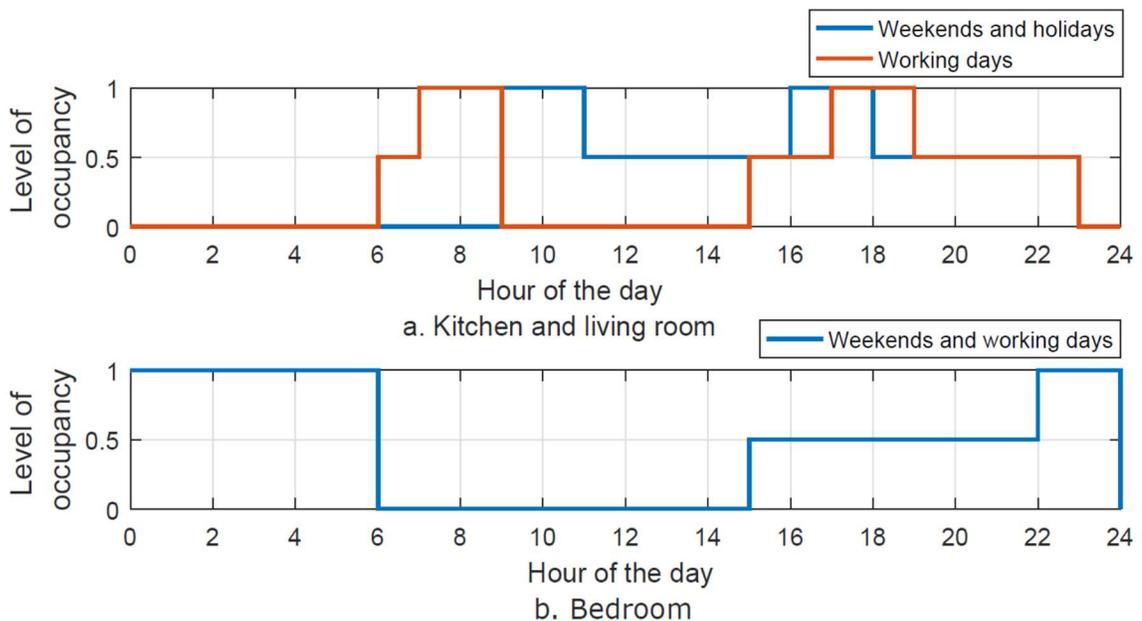
116 Relevant information about the ZEB dwelling was collected from the project owners.
117 Based on this, a reference model of the SFD and its energy supply system was developed using
118 the dynamic simulation tool IDA ICE 4.7 [17]. The performance of the reference configuration

119 was adjusted using the standard values, in accordance with the NS 3700 [7]. Standard values for
 120 the different parameters were used as a reference, and variations around these were then made
 121 based on the data found in the literature [7, 18].

122 The aim of this study was to investigate the influence of occupant behavior on energy use
 123 of the ZEB building and to identify the difference between the values recommended by standards
 124 and custom habit based energy use patterns. The literature review indicated that the most
 125 common occupant habits are associated with the windows openings – to improve indoor air
 126 quality, switching of lighting, use of electric appliances, and DHW needs. Therefore, the text
 127 below provides the details of the occupancy patterns and the models related to these elements.
 128

129 *2.1. Occupancy patterns*

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



134
 135 Fig. 1. Occupancy patterns

136 *2.2. Window opening model*

137 The literature review performed by Fabi et al. [19] highlighted that the window openings
 138 are influenced by many factors, which interact in complex ways. It is evident that the window

139 opening behavior has a very big impact both on the indoor environment and on the energy use to
140 maintain the desired indoor environment quality. The window opening is not only an important
141 determinant for ventilation, but it also has a direct impact on contaminant concentration levels
142 indoor [20]. The outdoor temperature, indoor temperature, relative humidity, and the indoor CO₂
143 concentration are found the most influencing variables in determining the opening/closing
144 probability [21, 22].

145 The research within the IEA – ECBCS Annex 8 [23] shows that in the temperature range
146 between -10°C and +25°C, there is a direct linear correlation between the window use and the
147 outdoor temperature. Similarly, the results of statistical analysis in Danish dwellings [24] shows
148 that there is a direct link between the windows opening behavior and the outdoor temperature.
149 Raja et al. find that a change in window opening start to occur at an outdoor temperature of 15°C
150 [25]. When the outdoor temperature was below this value, fewer windows are opened and
151 opposite when above 15°C. The results of Nicol showed good agreement with this [26]. However,
152 the study performed in [27] mentioned that the equations for comfort temperatures are different
153 when the building is being heated and when it is free-running, because the indoor temperature is
154 decoupled from the outdoor temperature by the heating controls. Therefore, the windows opening
155 could occur at a temperature of +10°C [28] as a marking point of the comfort temperature to the
156 outdoor temperature.

157 Anderson et al. [29] found that CO₂ concentration is the most important driver for opening
158 windows, while the outdoor temperature is the most dominant driver for closing windows. The
159 study of Jeong et al. [30] showed that in the non-heating period, occupants opened windows
160 longer and more frequently and it results in lower CO₂ concentration. The CO₂ concentration is
161 used as an indicator of the occupancy in the rooms where the measurements take place. If the CO₂
162 concentration is below 420 ppm, the window is closed. The value of 420 ppm is chosen based on
163 observations that the outdoor concentrations may reach levels of up to 400 ppm [22]. The upper
164 bound of CO₂ concentration is normally set to 900 ppm.

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

168 One aspect that affects the air change rate is how often and for how long the windows are
169 opened but also the degree of opening will have an impact [19]. Opening a window by more than

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

181 The model of the window opening control employed in this study was based on the
182 literature review and factors leading to opening and closing probabilities. The implemented
183 model for the window opening consisted of the five controllers based on the CO₂ concentration,
184 relative humidity, the outdoor temperature, the indoor temperature, and occupancy schedule. Each
185 control is IF-THEN type, depending what is the action. In some cases there are also some other limits as
186 explained below. Here is a brief description how each of them is working:

- 187 - *The CO₂ control* specified the upper and lower levels of the CO₂ concentration. The
188 values were set 400 ppm as the level of the outdoor CO₂ concentration and 900 ppm
189 for the maximum room concentration when occupants were in the room [32].
- 190 - *The indoor temperature control* aimed to decrease the room temperature if the indoor
191 temperature was higher than certain limit. The temperature in the kitchen ranged
192 between 18-21°C with the set point for the window opening of 19°C. For the living
193 room these values were 20 - 24°C and the set point for the window opening of 22°C.
194 For the bedroom, the range was 19 - 21°C and the set point for the window opening of
195 21°C. The room temperature control was coupled with the outdoor temperature sensor
196 that worked only if the outdoor temperature was lower than the indoor temperature.
197 This measure helped to avoid overheating during the summer days.
- 198 - *The humidity control* identified the upper and lower bounds for operation between 50
199 - 65%.

- 200 - *The occupancy level* - all the three controllers described above were depended on
201 occupancy in the zone. If the occupants were present the controller sent positive
202 signal, if not a negative signal was sent for the window opening.
- 203 - *The outdoor temperature control* operated only if the outdoor temperature was above
204 +12°C, since the literature review identified lower probability of windows opening in
205 the range of -15 - +10°C depending on investigated countries.

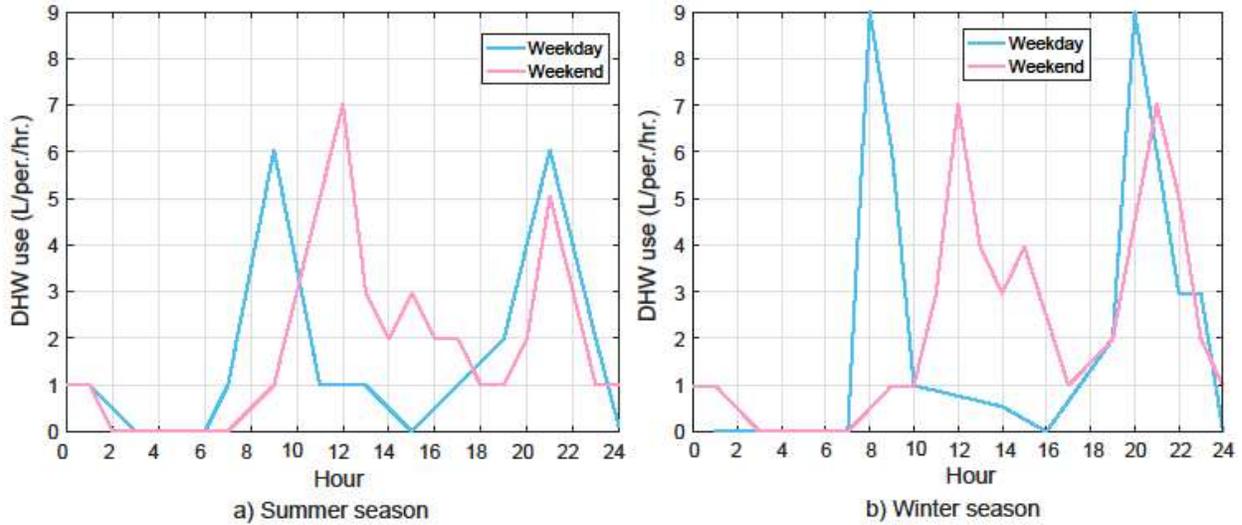
206 In addition, the special schedules for windows opening and closing was set for bedroom
207 and kitchen. Windows were opened in the evening and in the morning in the bedroom to get
208 some fresh air and in the kitchen when cooking took place. Since the window position is
209 important and effects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

212

213 2.3. *Model for the domestic hot water use*

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

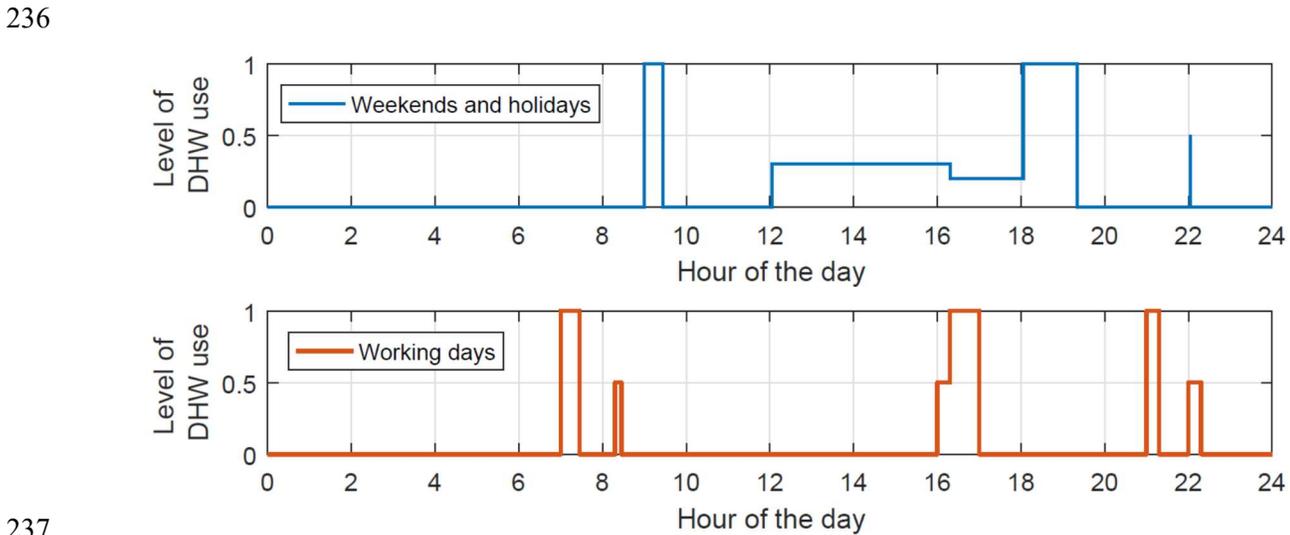
221 In order to make our study realistic, it was important to find relevant DHW profiles for
222 residential buildings. Different profiles for the DHW were found in the literature, but the most
223 relevant DHW profile was presented in a Finnish study [34]. The DHW profile analysis is based
224 on actual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



228
229 Fig. 2. DHW profile for four occupants in the residential building stock under two seasons

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

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



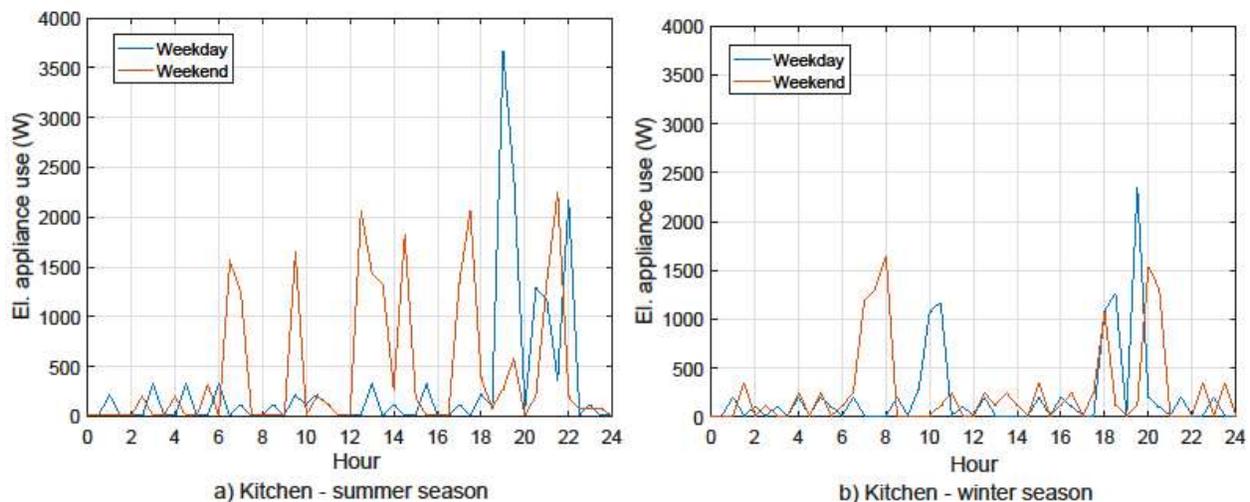
237
238 Fig. 3. Domestic hot tap water use profiles based on the standard values

239

240 The DHW was prepared and delivered by the energy supply system introduced in Section
241 3. The supply water temperature for the DHW was set to 55°C, based on the standard
242 requirements [37].
243

244 2.4. Model for use of electrical appliances

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



262

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		

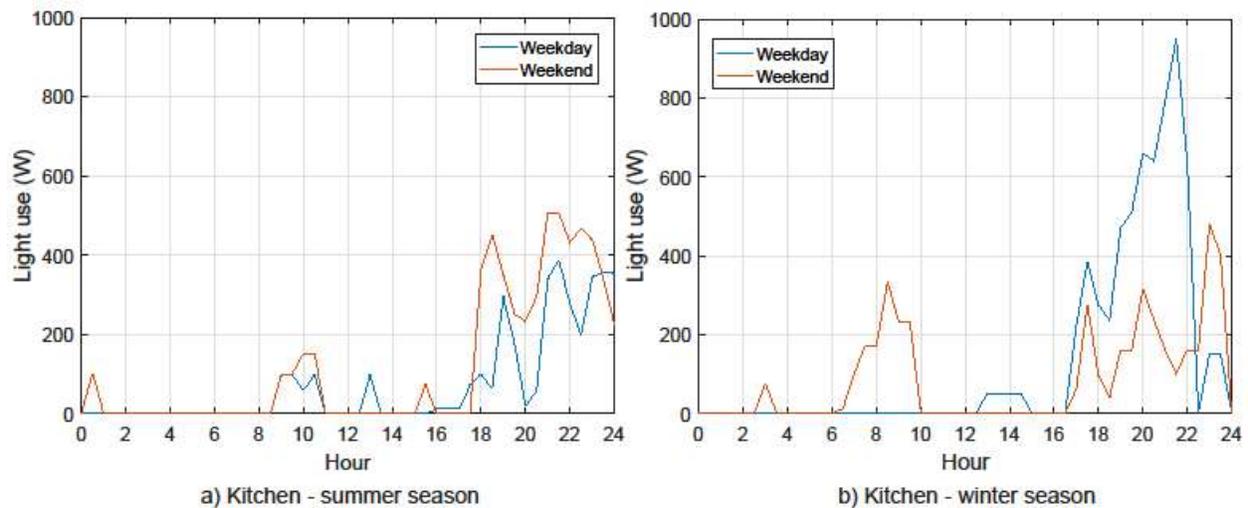
2.5. Light use model

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

287 illuminance is below the threshold then the resulting value of this test is 1, otherwise 0. In
288 addition, the occupancy in the zone was included in the model, leading to switching the light off
289 when nobody was present.

290 Another model of the domestic lighting was also implemented based on high resolution
291 lighting profiles generated with the help of the model described in [48]. The light model
292 described in [48] is developed by the same authors as the model for the electrical appliances [41]
293 and is also based on probability. The 1-min data was reduced to 30-min data and profiles were
294 generated for weekdays and weekend days depending on month and occupancy in the zone. Fig.
295 5 shows an example of generated light profile for kitchen under summer and winter seasons by
296 using the model described in [48].



297
298 Fig. 5. High resolution lighting model

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

300

301 2.6. Data analysis and the results presentation

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

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

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

$$311 \quad POW_{mis,i} = POW_{PV,tot,i} - POW_{con,tot,i} \quad (1)$$

312
 313 where $POW_{mis,i}$ (kW) is the power mismatch of the i th hour, $POW_{PV,tot,i}$ (kW) is the total hourly-
 314 average PV power generation of the i th hour, and $POW_{con,tot,i}$ (kW) is the total hourly-average
 315 building electricity use of the i th hour.

316 The annual energy balance reliability can be found as:

$$317 \quad \varphi_j = \frac{\sum_j^{8760} POW_{PV,tot,i}}{\sum_j^{8760} POW_{con,tot,i}} \quad (2)$$

318
 319 where, φ_j is the annual energy balance reliability of the j th year.

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

$$324 \quad S = STD \left(\frac{POW_{mis,i}}{\max[|POW_{mis,1}|, |POW_{mis,2}|, \dots, |POW_{mis,8760}|]} \right) \quad (3)$$

325

326 **3. ZEB demo building**

327 In this study, the influence of occupant behavior on a single-family demo dwelling (SFD),
 328 called “Multikomfort”, was analyzed. The building was constructed according to the Norwegian
 329 Zero Emission Building definitions with an ambition level of operation and material, and is
 330 located in Larvik, southern Norway. The annual average temperature in Larvik is 6.3°C. The
 331 house is a two-story home with a floor area of 202 m², and it was designed to accommodate a
 332 family of four to five members. The analyzed building is shown in Fig. 6. A detail building
 333 description and parametric study of the analyzed ZEB in Fig. 6 may be found in [16, 51].

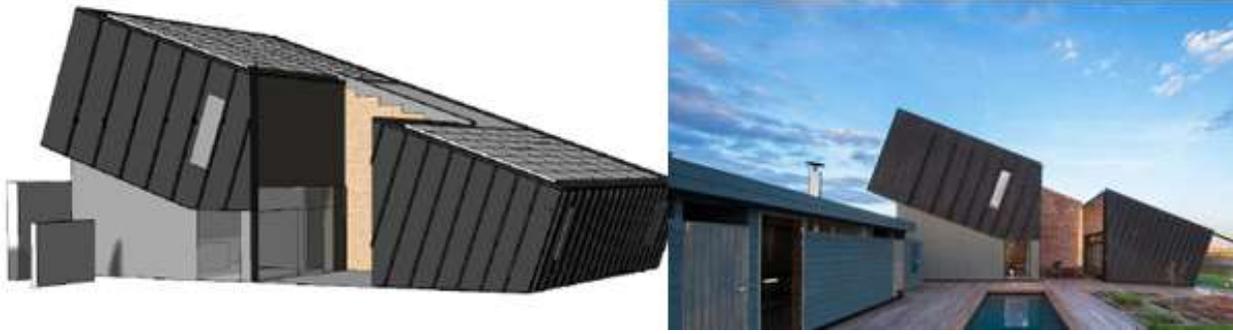


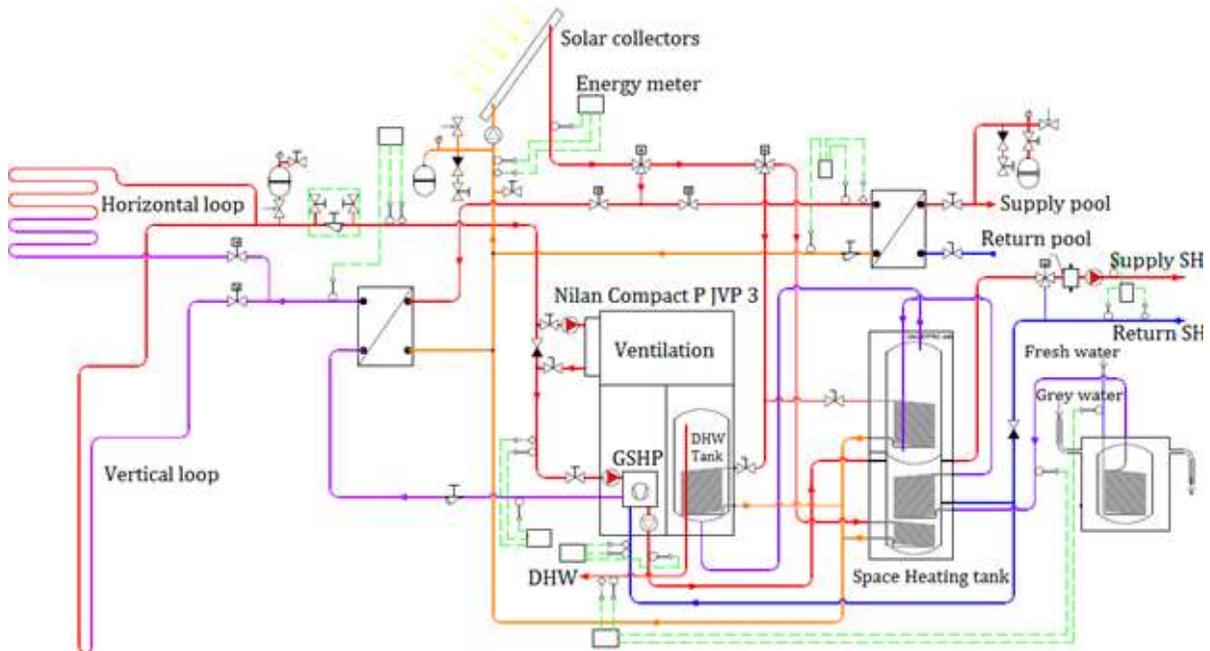
Fig. 6. Architecture of the SFD "Multikomfort" [52]

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/m²K.

Table 2. U-values and normalized thermal bridge values

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

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.



354

355

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

356

357

The implemented ventilation system was balanced mechanical Constant Air Volume (CAV) system. Flow rates were set to 240 m³/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/m²K.

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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%	

370

371 4. Results and analysis

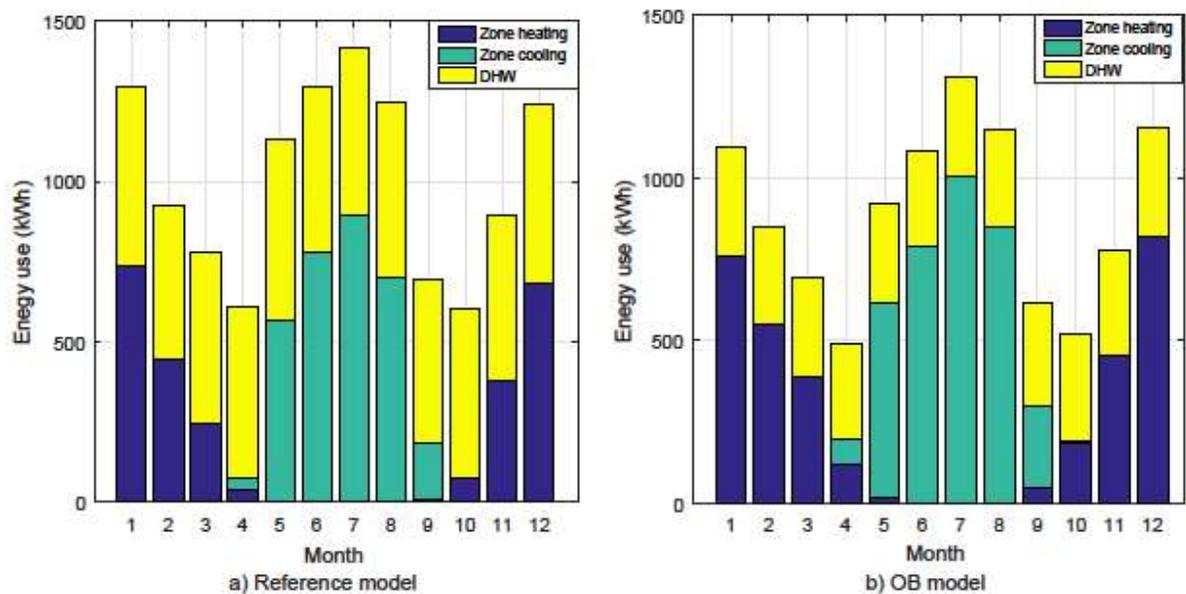
372 Influence of the occupant behavior on the ZEB performance is presented in this section.

373 The analysis of the influence of the occupant behavior included analysis of the following: heating
374 and cooling demand, indoor environment parameters, and electricity grid and grid interaction.

375 Result comparison of different approaches to model the occupant behavior is also given in the
376 section.

377 4.1. Influence of the occupant behavior on energy demand

378 First, Fig. 8 shows results on heating and cooling loads in the investigated ZEB. “OB”
379 shortcut is used to mark the results treating the occupant behavior. Maximum specific heating
380 demand was calculated, in accordance with the NS3700, to be 17.6 kWh/m².



381

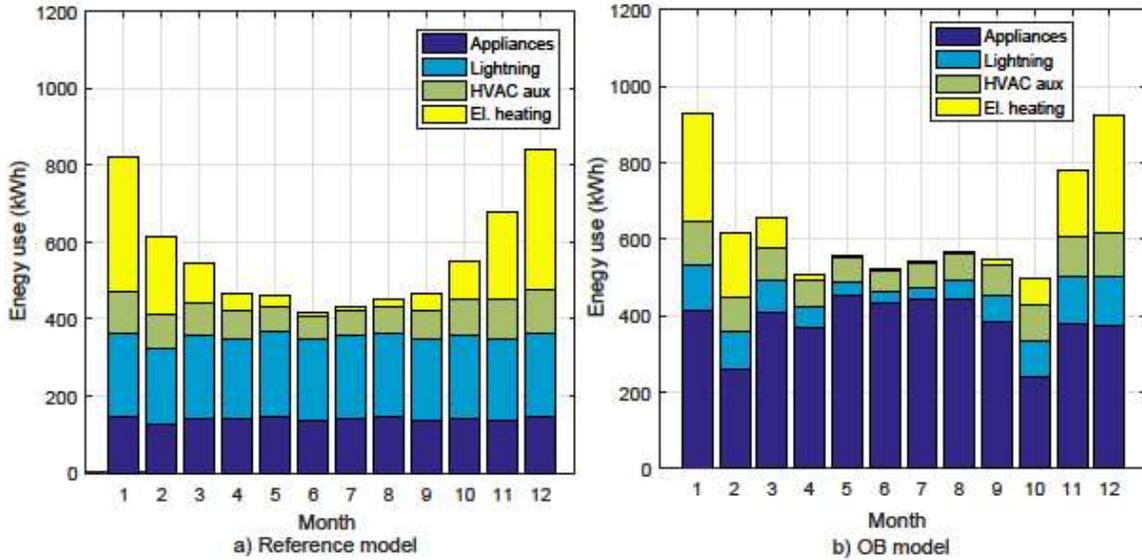
382

Fig. 8. Heating and cooling loads

383 From Fig. 8 it can be noticed that there is a difference between the results for the
384 reference case and the model treating the occupant behavior (marked with OB model). It was
385 found that DHW profiles suggested by Norwegian standard NS3700 [35] gave higher values for
386 the DHW energy use compared to the results obtained by using the occupancy profiles from [34].
387 The DHW model treating the occupancy resulted in 3745.1 kWh/year, while the reference case
388 based on the standard values gave 6368.7 kWh/year. The difference in these values was 70%.
389 This showed that the standard values may lead to oversizing the system and overestimating the
390 DHW energy use. The reason for this difference could be that the Norwegian standard NS3700
391 does not consider coincidence factor for the DHW use. The standard values for the DHW
392 considers that all the DHW taps would be in use. In practice, most of them are not in use. This
393 big difference in results might indicate that the standard treats coincidence factor to be 1, while in
394 practice for the DHW this factor is low. Further, the heating load in the occupancy model showed
395 higher values in comparison with the reference case. The heating load in the reference case was
396 2609 kWh/year, while when considering the occupant behavior it was 3347.2 kWh/year, that is
397 28 % more. The reason for this was that more heating was required when the windows were
398 opened during the winter season. Opposite happened for the cooling load that was 3959.7
399 kWh/year for the reference case and 3570 kWh/year when occupant behavior was considered.
400 This means that the occupant behavior introducing window opening decreased cooling load for
401 11 %.

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

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Fig. 9. Electricity energy use

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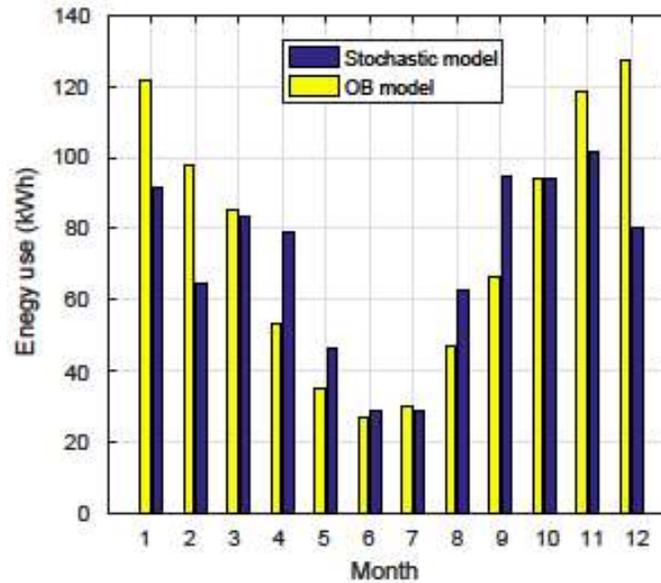
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Fig. 9 shows that in the reference case the lighting and equipment electricity use had a uniform distribution along the year. However, the detailed occupancy model resulted in much higher values for the appliances, but lower for the lighting. The reason 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.



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Fig. 10. Comparison of two lighting models

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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.

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4.2. Influence of occupant behavior on indoor air quality

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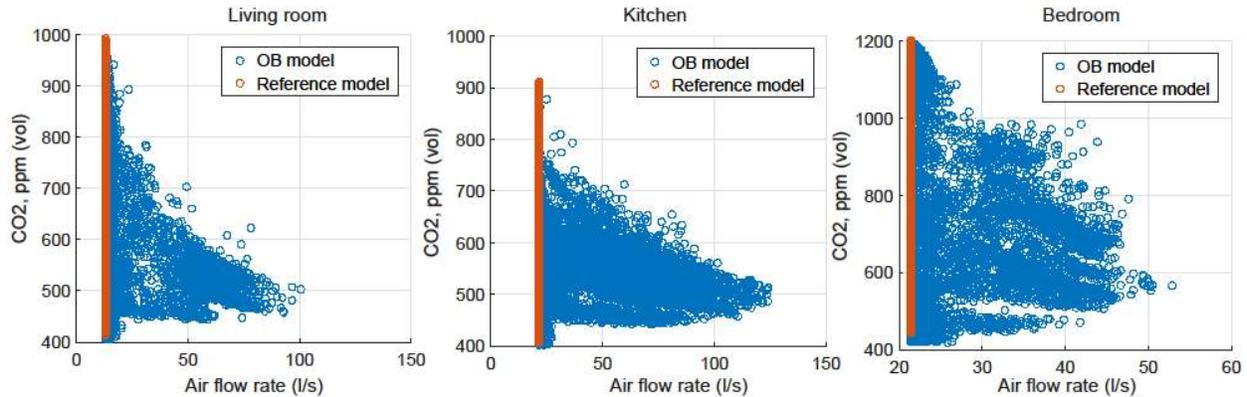
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The indoor air quality level is very important to consider in the ZEB, since it provides relevant information about human perception in the investigated building. The indoor air temperatures and CO₂ level are two important factors among many explaining indoor air quality and are given further. Fig. 11 shows CO₂ level versus air flow rate. Please note, that in Fig. 11 the

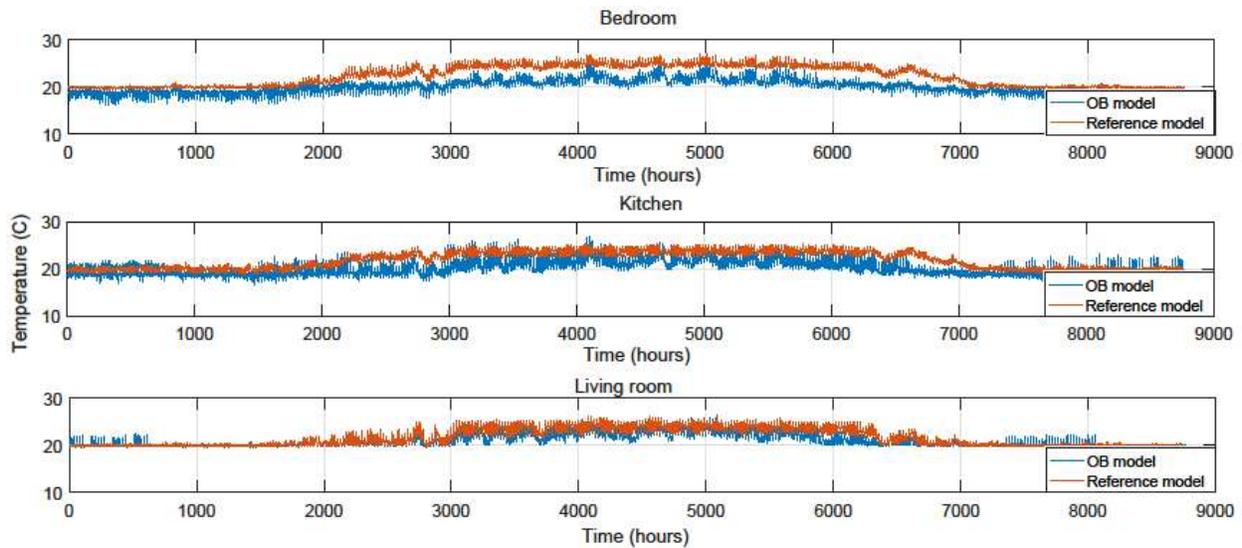
441 red color shows the results for the reference case, while blue color presents changes due to
442 occupancy activities, i.e. window openings.



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Fig. 11. Change in CO₂ level in zone

445 To recall in Fig. 11 for the reference case, the mechanical CAV ventilation was only
446 implemented. This resulted in the air flow rate of around 20 l/s depending on the investigated
447 zones, based on the standard requirements as explained in Section 3. However, when the
448 occupant behavior was considered, the results showed reduction of the CO₂ level with the
449 increase in the air flow rate. The air flow rate increased due to window opening. This fits well
450 with the human sensation and dissatisfaction of indoor air quality and the human reaction to open
451 the window if they feel dissatisfied. In the occupancy model, the CO₂ threshold was set in the
452 range of 700 – 1100 ppm for the mechanical ventilation. In Fig. 11 it can be noted that the upper
453 bound for the CO₂ concentration was reached only in the bedroom, when the room was not
454 occupied and the windows were not operated. However, while the bedroom was ventilated in the
455 evening and morning hours the CO₂ level decreased considerably due to window openings.
456 Further, the temperature fluctuation within the room was important to consider, since it indicated
457 achieved thermal comfort. Fig. 12 shows temperature distribution with and without considering
458 the occupancy model.



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Fig. 12. Temperature distribution in the zones

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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.

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4.3. Influence of window openings on heating and cooling demand

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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.

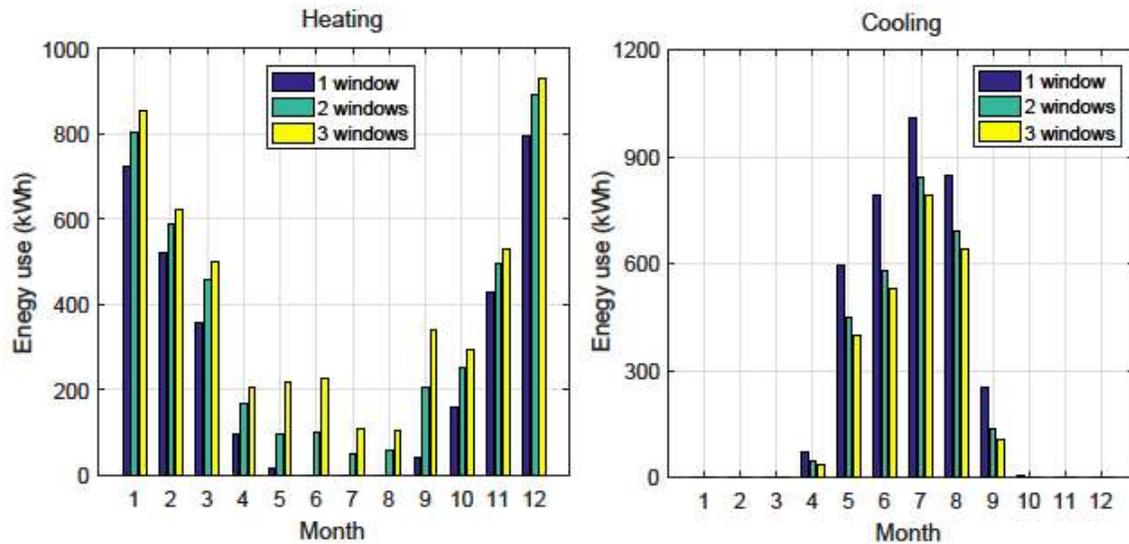


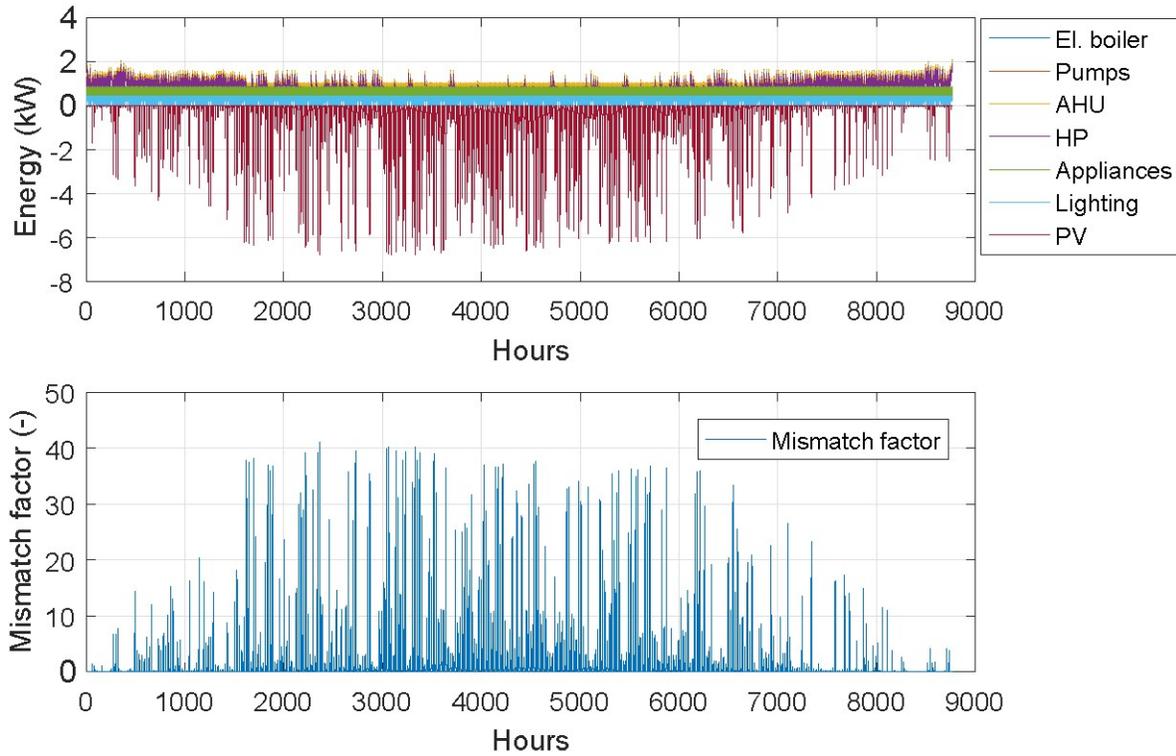
Fig. 13. Heating and cooling energy use depending on number of opened windows simultaneously

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

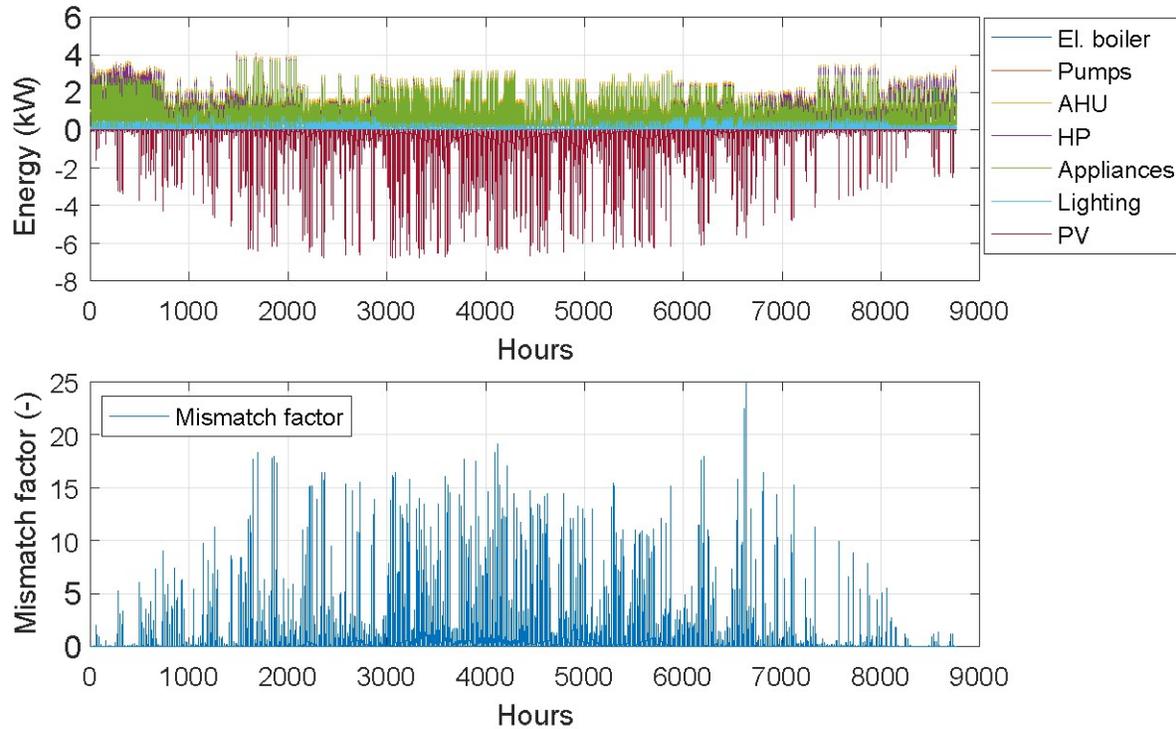
One of the most important questions when it comes to ZEB is the ability of a building to satisfy electricity needs with the help of installed PV system. Therefore, analysis of the ZEB influence on the power grid was performed. Due to intermittent power generation from the ZEB, the stress that could be 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.

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



495
496 Fig. 14. Electricity use, electricity production, and mismatch factor for reference model

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



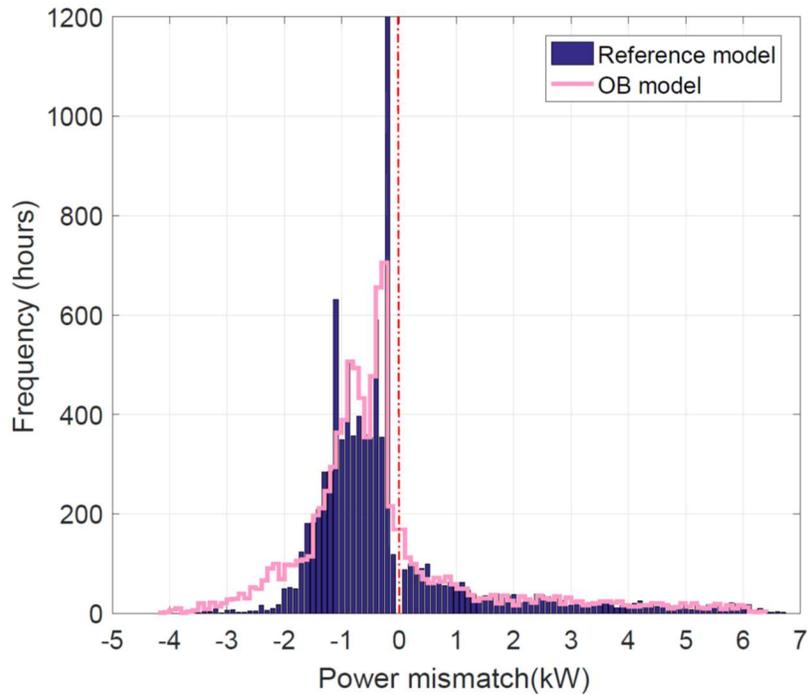
502

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

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

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

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



519

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

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

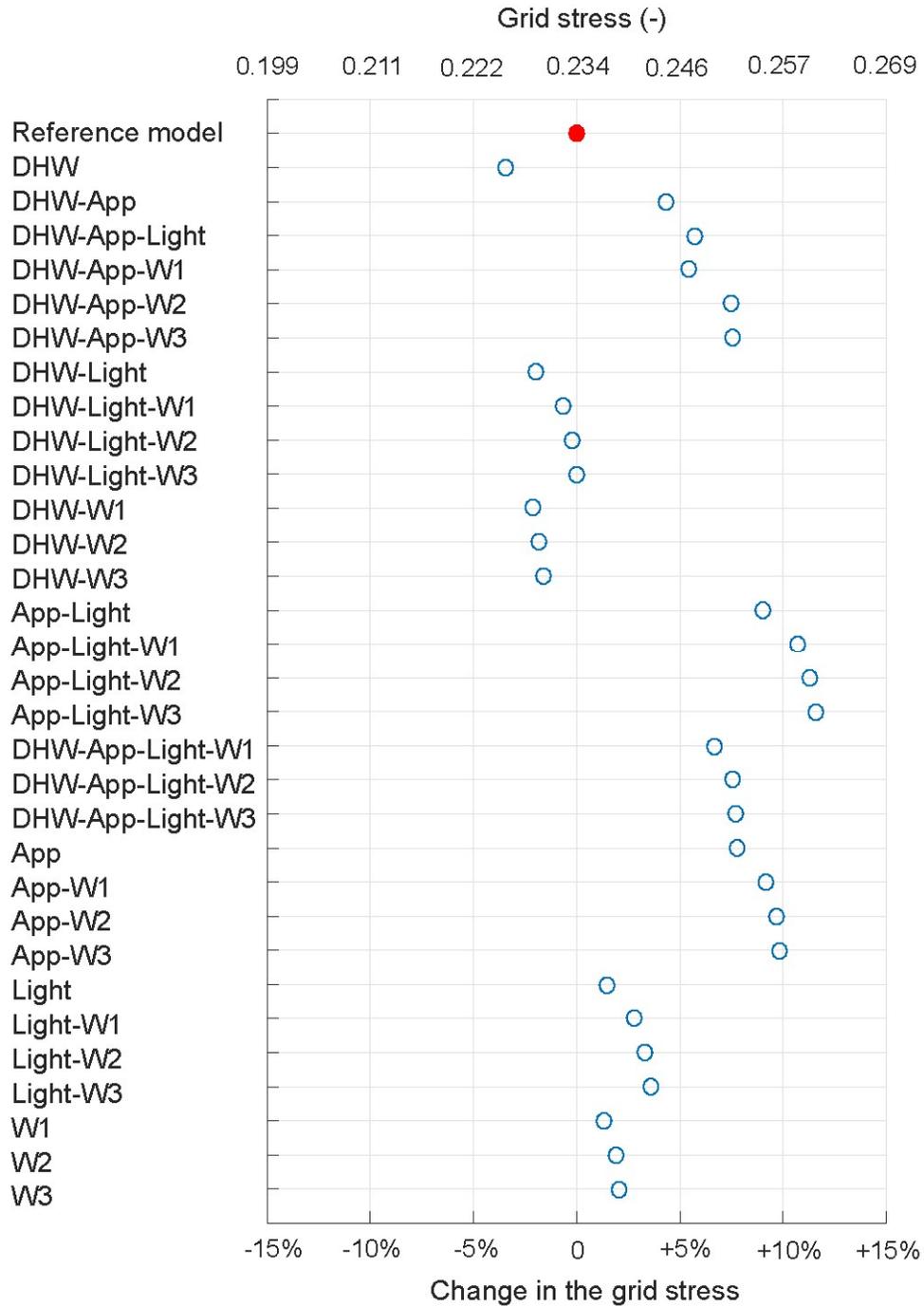
536 The grid stress as a result of different occupant behavior is shown in Fig. 17. In Fig. 17
 537 different shortcuts were introduced to present different scenarios to evaluate the effects of the

538 occupant behavior. In total 31 scenarios for different occupant behaviors were analyzed. A brief
 539 explanation for each scenarios is given in Table 4. In some scenarios the occupant behavior
 540 models introduced in Section 2 were used, while all the other parameters were kept as the
 541 standard recommendations.

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

Scenarios	DHW model	Electrical appliances 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

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Fig. 17. Grid stress

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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

550 building. The lowest grid stress was due to the use of the DHW. The influence of the occupant
551 behavior on the DHW use resulted in a low value for the grid stress, because the DHW was
552 mostly supplied from the solar collectors and the heat pump.

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

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

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

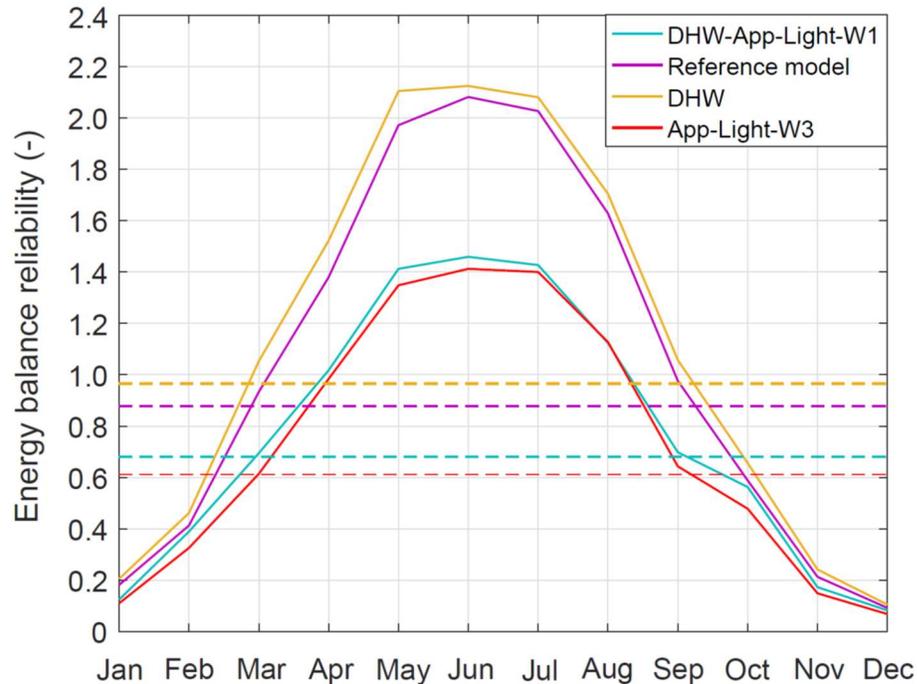


Fig. 18. Energy balance reliability

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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

591 would be fully considered. This explains the frequency diagram shown in Fig. 16 where the
592 number of positive hours is less than negative. From the other side, the annual value does not
593 provide indication about power fluctuations on hourly or daily basis, therefore, it is hard to
594 conclude that the installed PV area presents the best match between the supply and the demand.
595 The solution for this could be in installation of electric energy storage system for internal needs
596 during low solar irradiance hours.

597 **5. Conclusions**

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

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

616 The analyzed ZEB showed the annual energy reliability factor equal to 0.679 when all the
617 four components of the occupant behavior were considered, the correct DHW profiles, the
618 electrical appliance use, the lighting use, and the window openings. This value was by 22.5% less
619 than for the reference model. This means that the PV panel area would not be able to cover all the
620 electricity demand, if the occupants use of the ZEB was different than the standard values.
621 Consequently, the ZEB would not fulfill its definition. From the other side, the PV system is

622 normally sized to cover the average annual electricity demand. The solution for improving this
623 could be installation of a electric storage based on design requirements for such systems.
624 Consequently, the peaks would be shaved and the need in electricity supply from the grid would
625 decrease. Economic possibilities in transferring the generated electricity to the grid were not
626 investigated.

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

630

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636

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