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Energy performance evaluation of a nearly Zero Energy Building and the reasons for the performance gap between expected and actual building operation

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Abstract. As energy standards focus on reducing energy use in new buildings, attention is drawn to the gap between the expected and actual building operation and energy performance. This performance gap can be associated with the building construction, its systems, its unbalanced operation, the assumptions on occupancy profiles during the design phase, or the users' interaction with the systems' operation and control. This work focuses on a nearly zero-energy (nZEB) single-family house located in central Denmark. The analysis of indoor environment and energy use is based on year-long data monitoring. The reasons for the deviation between the expected and actual energy use are suggested. The indoor environmental quality is analyzed to verify the compliance with the standards. The European recommendation for the yearly primary energy use of new single-family houses is 50 – 65 kWh/m². For the current case, the simulation tool Be18 gives a result of 30.8 kWh/m² for the design phase. However, the actual energy use is measured to be 58.2 kWh/m². The sensibility of nZEBs to such imbalances can lead to houses that do not function as intended. It is thus crucial to investigate further the causes of these disparities in order to bridge the gap between expected and final energy use in dwellings.

1. Introduction

The European Union and building regulations increase their focus on the reduction of energy use and greenhouse emissions, and on the incorporation of renewable energy sources in the building sector, and especially in newly constructed buildings [1]. Hence, the need for a new generation of high-performance buildings with nearly zero energy use is strengthened. However, a performance gap between the predicted and real energy performance of the dwellings has been documented in multiple studies [2-7]. It shows that new buildings constructed in accordance with these standards can experience poor indoor environment, overheating and much higher energy use than expected [8].

This discrepancy can be connected to the assumptions made during the initial design phase, changes implemented during the construction phase, or to the operation of the dwelling. Many researches focused on the influence of human behavior and the challenges to achieve appropriate energy performance forecasting [9-13]. It is pointed out that more energy-efficient buildings are more sensitive to the influence of occupant behavior [9,11,14]. Different suggestions have been put forward in order to assess more accurately the building's actual performance. A reference occupancy and user behavior profile could be assigned, alongside the reference building model [10]. Additionally, reconsidering the energy demand calculation by the building regulations can have a significant impact on achieving nearly-zero energy buildings that perform as intended [9,11]. Finally, in order to achieve better prediction and obtain higher understanding of the occupancy patterns and behavior, it is necessary to perform extensive



occupant-related data collection, monitoring of real occupied buildings to get good insight about the performance gap [2,7,15]. Nevertheless, energy efficiency is not the only parameter that should be addressed when evaluating a building's performance. The indoor environmental conditions are an equally important aspect, with high complexity, where a similar mismatch can also be found [2]. The objective of this project is to tackle the challenges arising with the 2020 regulations and the new generation of dwellings trying to comply with them. Detailed monitoring and assessment of both the energy efficiency and indoor environment are intended to address these issues.

2. Case study

2.1. Building description

The studied building is a detached one-story, single-family house, located in Ry, in central Denmark. The building was constructed at the end of 2017 and is characterized as a nearly zero energy building, based on the Danish energy labeling standards [16].

The dwelling has a total floor area of 160 m². It is constructed on two levels, with a height difference of 0.5 m. It includes 4 bedrooms, 2 bathrooms, 1 kitchen, 1 dining area, 1 living room, and a utility room. The kitchen, dining area and living room are connected to form an open space. There is also an unheated storage space attached to the building. There are windows towards all directions, while the openings in the South, East and West façades are equipped with sunscreens. Figure 1 shows the plan of the dwelling, while Figures 2 and 3 give an external view of the house.

The characteristics of the building study case are summarized in Table 1. The building is occupied by a young couple. The windows are triple-pane low-energy windows, with high light transmittance and low solar heat gain factor.



Figure 1. Floor plan of the study case.



Figure 2. External northwest view.



Figure 3. External south view.

Table 1. Characteristics of the construction elements.

Building description	
External walls U-value [W/m ² K]	0.15
Roof U-value [W/m ² K]	0.09
Ground slab U-value [W/m ² K]	0.08
Windows U-value [W/m ² K]	0.9
Windows g-value [-]	0.49
Air tightness n ₅₀ [l/s m ²]	0.52

2.2. System description

The building is equipped with a floor heating system connected to district heating and a compact ventilation unit, which is also providing sanitary hot water. The compact ventilation system has an integrated air-to-water heat pump and a counter-flow heat exchanger with 85% efficiency. The domestic hot water is primarily produced by the ventilation unit through the recovered energy from the exhaust air, and supplemented by an auxiliary electrical heater. The ventilation control is based on indoor CO₂ and relative humidity levels. Ventilation operation can be controlled individually for each room and based on occupancy schedules. When the building is not occupied and the indoor conditions are adequate, the system runs with a minimum airflow rate of approximately 0.15 l/s m², compared to 0.3 l/s m². The ventilation set-points are summarized in Table 2.

Table 2. Ventilation control set-points.

	Damper opening	Damper closing
CO ₂ [ppm]	900	700
Relative humidity [%]	70	50
Relative humidity – bathroom [%]	60	50

Natural ventilation and sun protection can be activated in order to create a pleasant indoor environment and minimize energy usage. Natural ventilation can be achieved through the skylights and a novel ventilation system with louvers incorporated in several windows in rooms with overheating risk. The external solar shadings are installed at the windows of the master bedroom and living room, with east, south and west orientations. In order to encourage the use of these systems, the solar shades are designed so that they allow good view to the outside, even when activated, while the ventilation louvers are providing theft and rain protection so that they can be used even when the dwelling is not occupied. In Figures 4 and 5 are shown the ventilation louvers and solar shades. At the end of November 2018, the natural ventilation and sun protection systems were connected to the control system, so that they can be

automatically controlled. The examined period for this report only covers the period with manual activation of these systems.



Figure 4. Ventilation louvers.



Figure 5. Solar shades and view to the outside.

2.3. Data monitoring

The data logging started in November 2017 and is still ongoing. This paper analyzes the data collected during the entire year of 2018. The measurements are recorded every 5 minutes in all rooms of the dwelling and include cold and hot water consumption, energy use for heating, ventilation, production of sanitary hot water, the status of the storage tank, the heat pump, as well as electricity use for all appliances. The operative temperature, CO₂ and relative humidity levels are monitored in all rooms. Additionally, the airflow, temperature of supply and return hot water, fan speed and damper opening in the ventilation unit are recorded. All measurements are performed by state-of-the-art sensors commonly used for indoor climate monitoring, electricity and heating metering in buildings.

3. Methodology

Over the entire period of the building's design, construction and occupancy, it has been undergoing a commissioning process to reassure its proper operation, as initially intended. During this process, a continuous readjustment of the systems' operation has taken place and correction of mistakes made during design or construction. Not all measurements have been available from the beginning, therefore the presented results include only the information that has been accessible during the period of study and is within the scope of this analysis.

The commissioning of the building has revealed several issues that had to be adjusted, revised or improved. For example, in June, it was noticed that a valve in the sanitary hot water loop was constantly open, even though it was not necessary, resulting in increased energy used for heating. Changes in the monitoring system have resulted in some missing values. The external sun shades were not installed until March 2018. The user control system, with which the occupants can automatically control or overwrite the different systems of the house, was activated at the end of October 2018.

Finally, during the data analysis process, some problems were observed. Therefore, additional sensors (IC-meters) were installed right beside the building sensors, with the purpose to verify the data accuracy. It was observed that monitored CO₂ levels and relative humidity values from the building sensors were not reliable. The sensors were installed at the end of June in the kitchen and living room. In this paper, values for CO₂ and relative humidity analysis are only those from the IC-meters for July to December. The aim is the long-term assessment of indoor environmental quality and energy use of the dwelling. Furthermore, the monitored data analysis aims to reveal mismatches between the intended and actual operation of the systems and equipment.

The evaluation of the indoor environment is done on room level, considering the most used rooms: master bedroom, living room, and kitchen / dining room. The thermal comfort categories are taken for

winter and summer conditions, with January, February, March, April, October, November and December considered winter months, and May to September as summer. Also, from the 10th to the 24th of July, the tenants were on holiday, therefore the building was not occupied.

4. Results and discussion

4.1. Energy use

Through analysis of the monitored values, the energy needs of the building are assessed and the actual yearly energy use is compared to the expected one. Figure 6 presents the measured monthly delivered energy for heating, ventilation and production of sanitary hot water, as well as the total electricity use. The electricity use of the compact ventilation unit is shown both as part of the total electricity use and separately, as it accounts for 47% of the total amount. The rest of the electricity use is given by the white goods (cooking plate, refrigerator, dishwasher, cooker – for boiling water, washing machine and dryer), storage tank, floor heating pump, control system, and all the rest connected to the occupants' activities (household appliances and lighting). The white goods contribute to the total amount with 29%, the control system with 11%, and the storage tank and floor heating pump with 10.5%. A more detailed analysis of the electricity use by the different appliances can be found in the study of Carpino et al. [17], conducted for the same building.

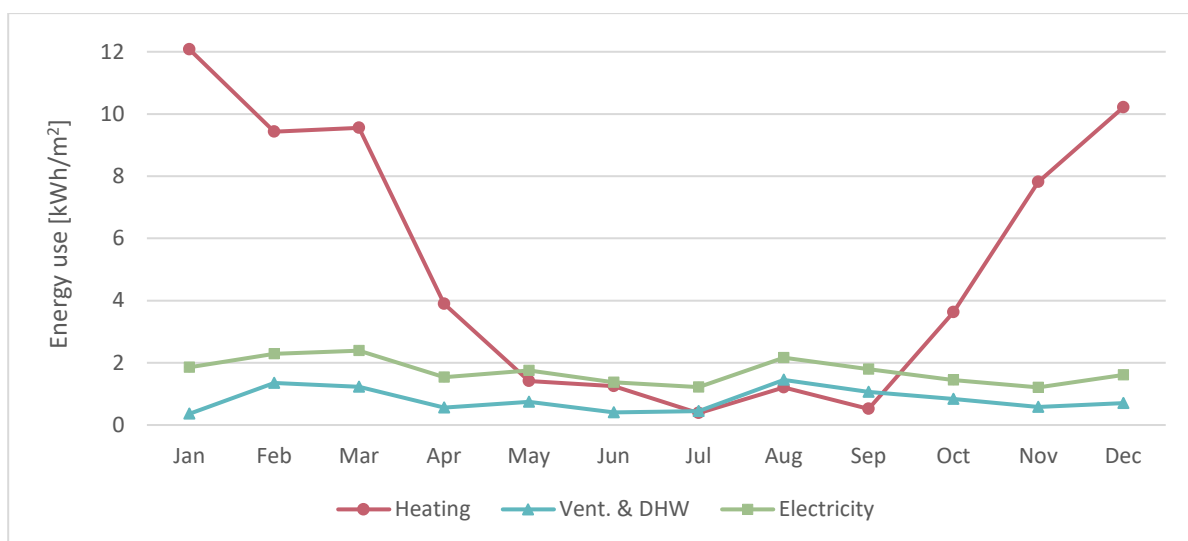


Figure 6. Energy use in 2018.

In order to compare these values with the numbers given by the European standards and simulation tool Be18 (which was used to calculate the total energy requirement during the design phase), the conversion from delivered to primary energy use is made with a primary energy factors in Denmark of 1.8 for electricity and 0.6 for district heating. The results are summarized in Table 3. As one can see, the total energy use of the building for heating, cooling, ventilation and hot water is higher than expected by 89%. This mismatch may be due to several reasons. Firstly, simulation program Be18 is not meant for detailed energy analysis, but rather as an estimation of the energy frame, using a standard occupancy profile [17]. Additionally, during the design phase, assumptions had to be made, which in several cases might have been quite far from the reality. Finally, during the first year, the building's operation does not comply entirely with the intended, due to necessary adjustments or corrections to the systems, and also due to the fact that some of the equipment or control has not been implemented yet. On the other hand, electricity use is much lower than expected, resulting in smaller internal gains and thus higher heating needs. In [17], it was estimated that the reduced effective heat gains from people and equipment load could explain an increase in the heating energy use of about 10 kWh/m² per year.

Table 3. Primary energy consumption [kWh/m² year].

		Measured energy use	Primary energy use	Be18 ^a	Commission recommendation ^b	
Electricity	Heating	61.4	36.8	58.2	30.8	50 - 65
	Ventilation & DHW	9.7	17.5			
	Tank & heat pump	2.2	3.9			
	White goods	6.1	10.9	15.8	54.8	
	Control	2.3	4.1			
	Other consumption	0.4	0.8			
Total		82.1	74	85.6		

^a Energy frame BR 2015/ 2018^b (EU) 2016/ 1318

4.2. Indoor environment

When evaluating energy use, indoor environmental quality (IEQ) should also be considered. IEQ is assessed based on thermal and atmospheric indoor climate only. In Tables 5, 6 and 7, the time distribution in different comfort categories is presented. The categories for the different parameters are given in Table 4, as they have been formulated based on the Danish standards [18]. The percentages in each category are calculated for the period that each room is expected to be occupied. Therefore, the time between 7:00 to 17:00 is taken as unoccupied, while for the living room and kitchen the considered period is between 17:00 – 23:00, and for the bedroom between 23:00 – 7:00.

Table 4. Thermal comfort and indoor air quality categories.

	Temperature in Summer [°C]	Temperature in Winter [°C]	CO ₂ above outdoor level [ppm]	Relative humidity [%]
IV+	27 < t	25 < t	> 800	70 < t
III+	26 < t ≤ 27	24 < t ≤ 25	800	60 < t ≤ 70
II+	25.5 < t ≤ 26	23 < t ≤ 24	500	50 < t ≤ 60
I	23.5 ≤ t ≤ 25.5	21 ≤ t ≤ 23	350	30 ≤ t ≤ 50
II-	23 ≤ t < 23.5	20 ≤ t < 21	-	25 ≤ t < 30
III-	22 ≤ t < 23	19 ≤ t < 20	-	20 ≤ t < 25
IV-	t < 22	t < 19	-	t < 20

Table 5. Time distribution in thermal comfort categories [%].

	IV-	III-	II-	I	II+	III+	IV+
Master bedroom	4.9	14.0	9.3	66.0	1.5	1.3	3.1
Living room	0.6	6.1	9.9	58.7	15.9	4	4.8
Kitchen / dining room	0.7	5.2	6.9	52.6	10.7	14.5	9.4

As one can observe in Table 5, thermal comfort remains in Category I and II during most of the time, with 77% and 85% for the bedroom and living room, respectively, while in the kitchen / dining room a percentage of 70% is achieved. In Figure 7, the aforementioned categories are divided into winter and summer period, in order to create a better visualization of the situation. It is worth mentioning that during

the heating period, the achieved thermal comfort level is very high. That is not exactly the case for the kitchen / dining area, where the large glazed areas towards the east and west can create a bit of overheating, even during the winter. Nevertheless, a decrease in the temperature set-point could be suggested, in order for the energy consumption for heating to be reduced. On the other hand, during summer, the temperature in the bedroom and living room seem to be quite low. It can be concluded that during the cooling season, the occupants prefer lower temperatures in the bedroom, which is probably achieved through the opening of windows at night time. Consequently, the temperatures in the living room and kitchen are also affected by these practices.

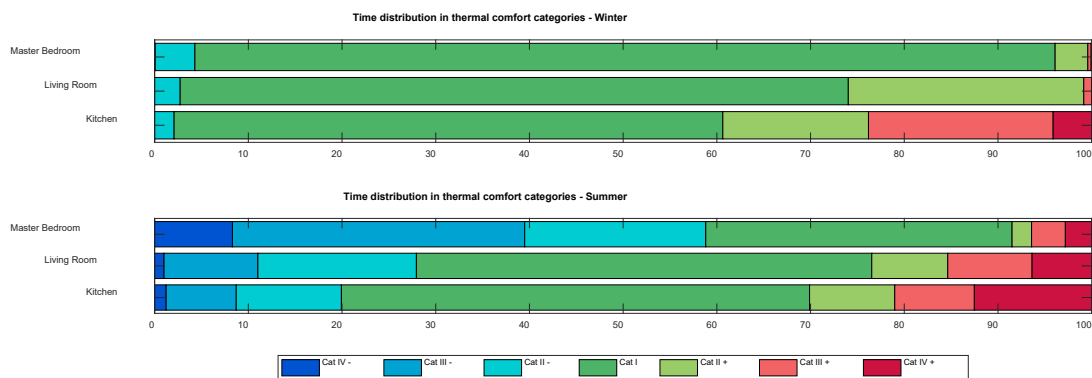


Figure 7. Time distribution in thermal comfort categories for winter and summer periods [%].

Regarding indoor air quality, CO₂ and relative humidity levels do not deviate much from Categories I and II. It can thus be concluded that the ventilation could be decreased significantly in the living room and kitchen without compromising the indoor air quality.

Table 6. Time distribution in comfort categories for CO₂ concentration [%].

Sensor	Room	I	II	III	IV
IC-meters	Living room	94.4	3.9	1.6	0.1
	Kitchen / dining room	95.7	3.0	1.2	0.1

Table 7. Time distribution in comfort categories for relative humidity level [%].

Sensor	Room	IV-	III-	II-	I	II+	III+	IV+
IC-meters	Living room	0.0	0.5	11.3	78.5	9.8	0.0	0.0
	Kitchen / dining room	0.0	3.5	12.5	77.0	7.1	0.0	0.0

5. Conclusion

Within the building industry, it has been broadly documented that there is a mismatch between the theoretical and real building energy performance, resulting in higher energy use than expected. This performance gap gives a distorted image of achievement concerning the energy reduction targets set by the European Union and building regulations. Additionally, this problem can create distrust between engineers and clients, and reluctance towards future technologies and practices [2]. In order to mitigate the problem, it is necessary to look into the reasons causing it and find ways to address these issues. Through this analysis, it has been concluded that the imbalance is the result of the combination of three factors. The first one is the use of theoretical profiles and assumptions made during the initial stages of design, in order to calculate the expected energy use. In the present study this account for about 1/3 of the deviation (10kWh/m² per year of primary energy). The second factor concerns the errors commonly

made during the construction and installation phase and the necessary adjustments and tuning of the systems so that they will perform as intended. These include set-point regulation, control methods, commissioning, verification, calibration or replacement of the different sensors. Finally, one of the most critical parameters is the occupants' behavior and practices. Even though the systems and automations might be operating perfectly, if the users' daily actions do not comply with energy efficiency practices, the result might be the opposite than intended. Especially when it comes to high energy performance buildings, which are more sensitive to the user's behavior. Therefore, set-point interference, window opening, or overwriting of the automatic controls can have a large impact on energy use, as well as IEQ. To bridge the performance gap, further analysis of these practices is needed to identify their impact on the building energy.

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